Phase-change Reconfigurable Optical WavEfront Synthesis System (PROWESS)

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Thermal modeling / characterization/ applications

MIT Team

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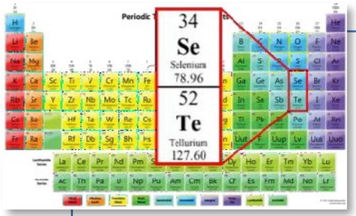
PCM & metasurface optics

MIT LL

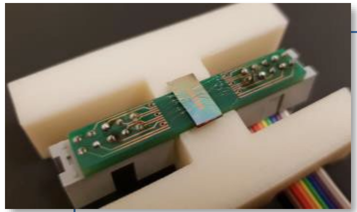
- Dr. Steven Vitale

Heater fabrication

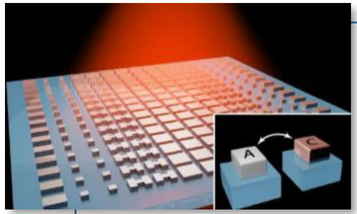
Outline



Reshaping light using PCM metasurfaces



Electrical switching of PCM metasurfaces



PROWESS for NASA scenario

Status and path forward to real-world application

PROWESS – Motivation

- Active wavefront control is a critical concept in a variety of optical systems, and the ability to on-the-fly tailor an optical wavefront has far-reaching implications.

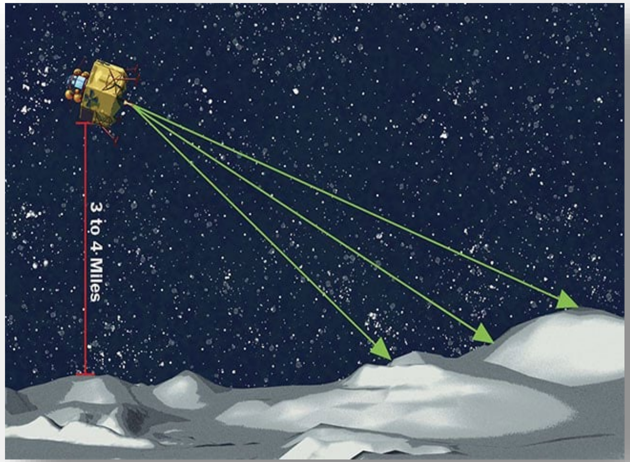
- Wavefront correction is currently limited to reflective technologies such as deformable mirrors that are bulky, expensive, and mechanically complex.

- Other methods of tailoring optical wavefronts have been explored, such as plenoptic imaging; however, these are fixed configurations that must be tailored for targeted applications and require computationally expensive image processing.

NASA Mission Need

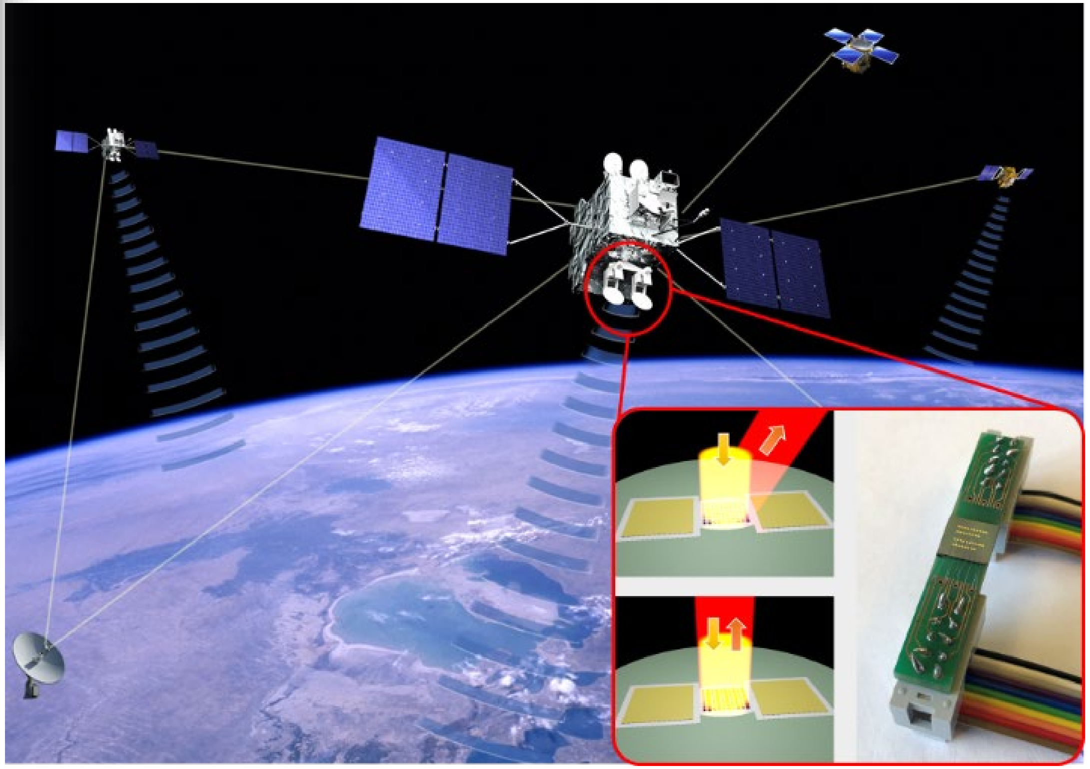
Metasurface-based optics capable of generating actively-tunable, arbitrary optical wavefronts at ultrafast speeds, with subwavelength resolution, and without moving parts.

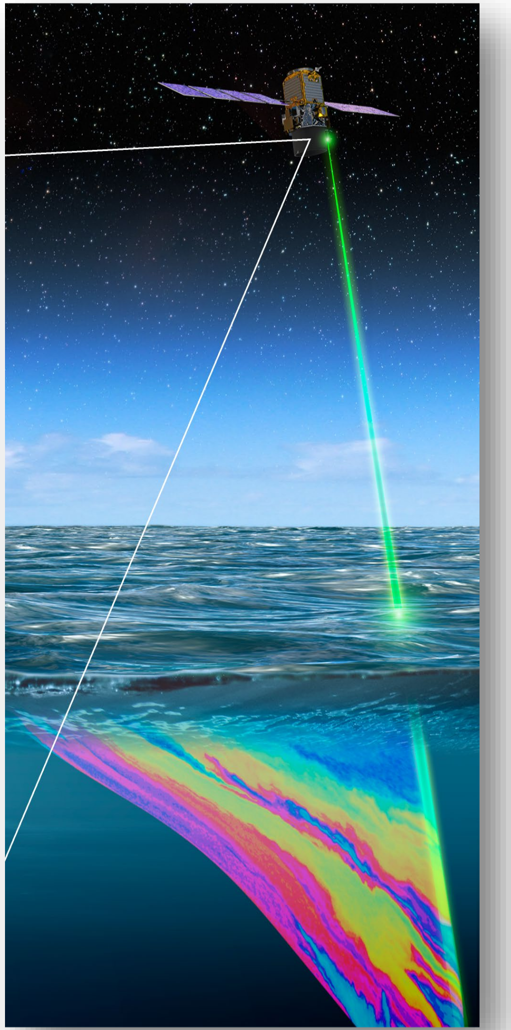
Reconfigurable planar optics for wavefront correction and beam steering



Navigation Doppler Lidar

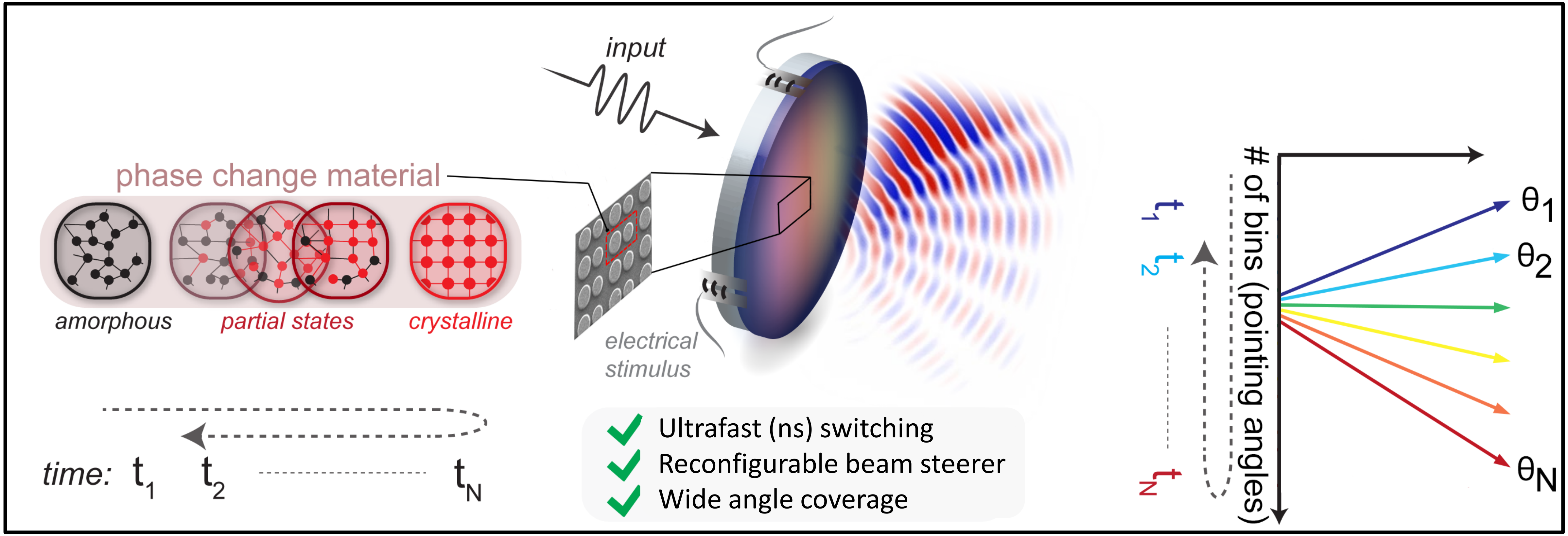

Space station docking system


Free space optical communication


Ocean surface LIDAR
Credit: NASA

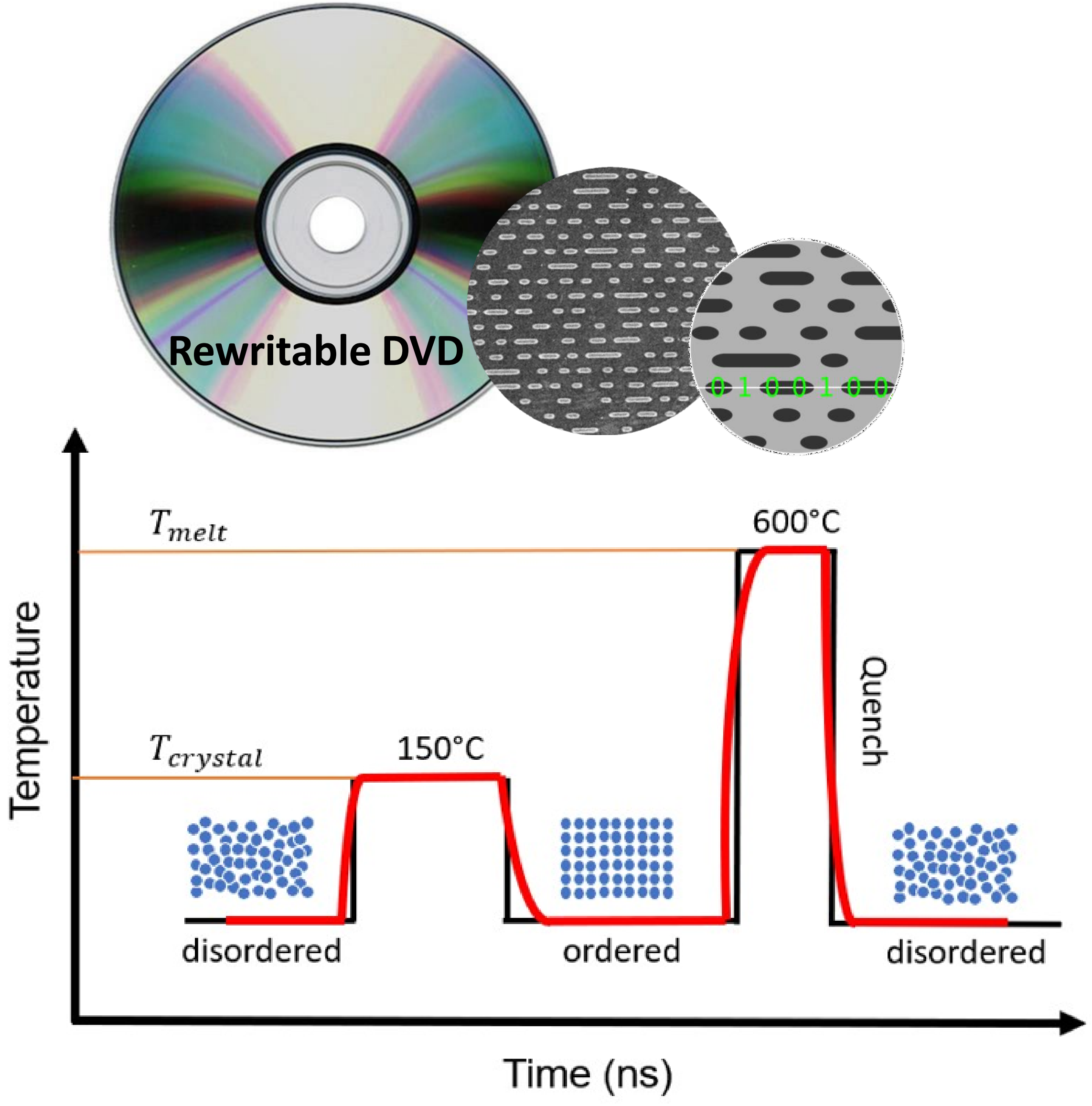
PROWESS is based on an optical metasurface

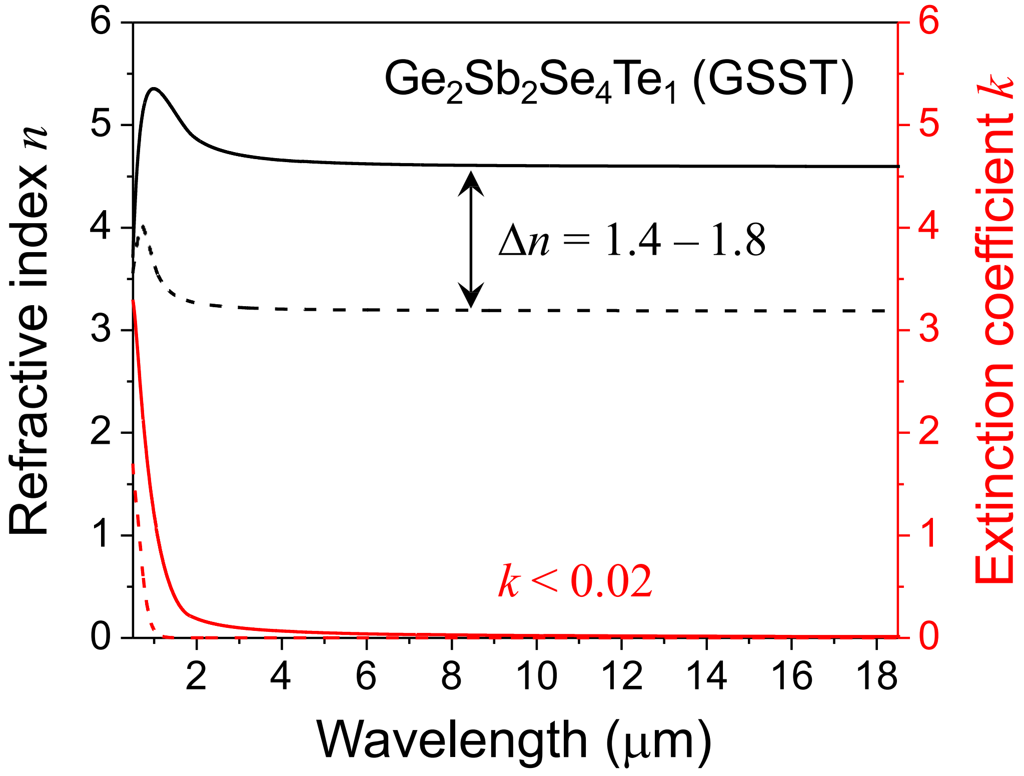
✓ manipulates light via spatially-arranged subwavelength nanostructures made from PCMs
active wavefront control by tailoring the phase of each constituent nanostructure



NASA invention disclosure #20255-1 "PCM-based metasurface Optical Phased Array (P-OPA) for eliminating detector saturation and ringing of lidar"

Phase change materials are core of the technology





✓ Index change: Δn = 1.4 – 1.8

✓ Loss: k < 0.02

Ref*Opt. Lett.* **43**, 94 (2018);
Nat. Commun. **10**, 4279 (2019);
J. Of Physics: Photonics **3.2** (2021) 024008

Type	Material or mechanism
Mechanical	Displacement
	Elastic deformation
	MEMS actuation
Free-carrier density modulation (electrical injection)	Semiconductors (junction biasing)
	TCOs (field gating)
	2D materials (field gating)
Thermo-optic	Semiconductors (thermal free-carrier refraction)
	Semiconductors or dielectric materials
Electro-optic	Electro-optic polymers
	Electro-optic crystals
	Liquid crystals
	Semiconductor multi-quantum-well (quantum-confined Stark effect)
Phase transition	VO_2
	Chalcogenide PCMs
Electrochemical	Electrochromic polymers
	Ionic conducting oxides (protonation)
	Ionic conducting oxides (lithium intercalation)
	Metal electrodeposition
Chemical	Metals (hydrogenation)
	Cover material addition/removal
Magnetic	Magneto-optical oxides
All-optical	Kerr nonlinearity
	Free-carrier injection

nature photonics

Review Article https://doi.org/10.1038/s41566-022-01099-4

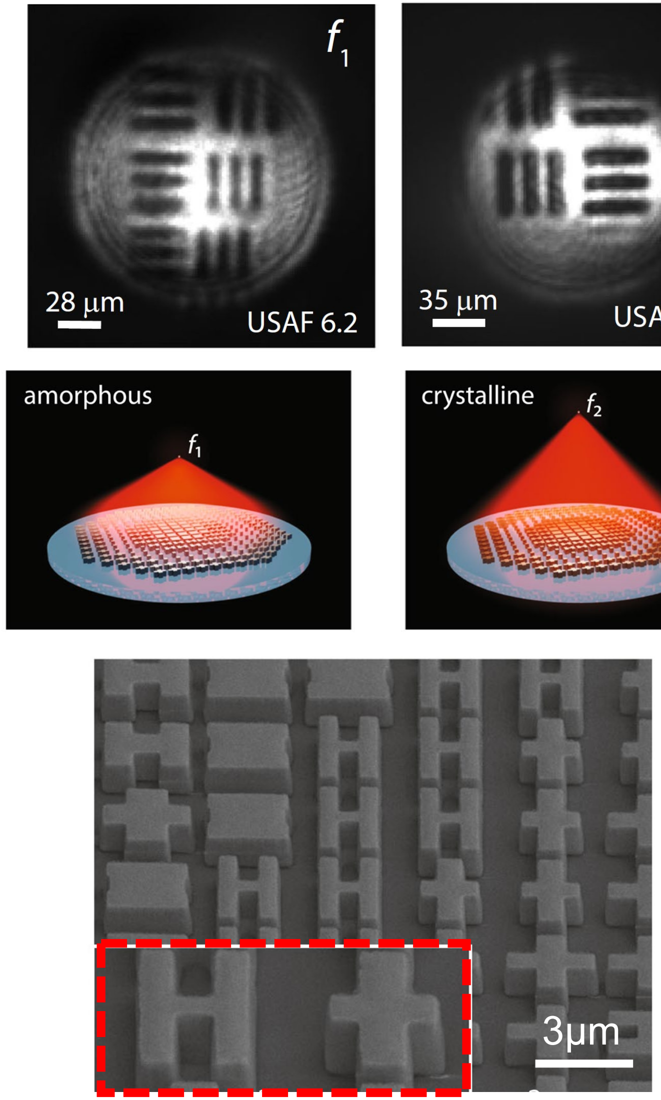
Reconfigurable metasurfaces towards commercial success

Received: 6 June 2022

Tian Gu [1,2], Hyun Jung Kim [3,4], Clara Rivero-Baleine [5] & Juejun Hu [1,2]

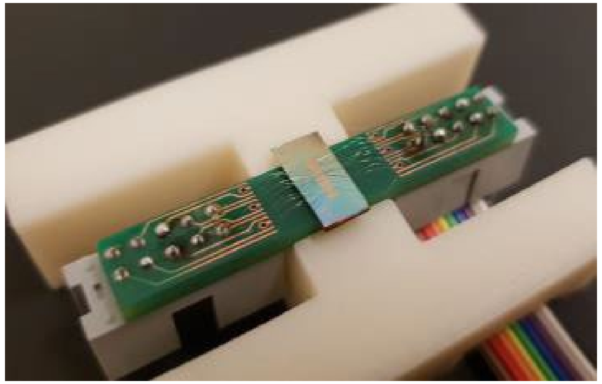
Application	Tuning scheme	Optical tuning parameter (phase/amplitude)	Optical contrast (relevant metrics)	Optical loss suppression	Endurance (cycling lifetime requirement)	Speed (bandwidth requirement)	Power consumption
Tunable filters for multispectral sensing	Continuous	Amplitude	✓ (extinction ratio)	–	– (10^{7})	– (1 kHz)	–
Beam steering for LiDAR	Continuous	Both	✓ (full 2π phase tuning range)	✓	✓ (10^{9})	– (10 Hz)	–
Light field display	Continuous	Both	✓ (FOV and image contrast)	✓	✓ (10^{10})	– (30 Hz)	✓
Computational imaging	Discrete	Phase	✓ (full 2π phase tuning range)	–	✓ (10^{10})	– (100 Hz)	–
Optical neural network with adaptive network training	Continuous	Both	✓ (full 2π phase tuning range)	✓	– (10^{8})	– (1 kHz)	✓
Dynamic projection display	Continuous	Amplitude	– (images contrast)	✓	✓ (10^{10})	– (30 Hz)	✓
Electronic paper (reflective display)	Discrete or continuous	Amplitude	– (colour saturation and image contrast)	–	– (10^{7})	× (1 Hz)	× (non-volatile or capacitive)
Zoom lens	Discrete or continuous	Phase	✓ (full 2π phase tuning range)	✓	– (10^{5})	× (1 Hz)	×
Digital signal modulation for free-space communications	Discrete	Either	✓ (modulation contrast)	✓	✓ (10^{18})	✓ (10 GHz)	✓
Adaptive optics	Continuous	Phase	✓ (full 2π phase tuning range)	✓	✓ (10^{10})	– (100 Hz)	×
Non-reciprocal optics based on spatiotemporal modulation	Discrete	Either	– (isolation ratio)	✓	✓ (10^{18})	✓ (10 GHz)	✓
Optical limiter	Discrete	Amplitude	✓ (extinction ratio)	✓	× (application-specific)	✓ (>1 GHz)	× (non-volatile)
Adaptive thermal camouflage	Continuous	Amplitude	✓ (dynamic range)	×	– (10^{8})	– (10 Hz)	×

PCM metasurfaces promise reconfigurable optics

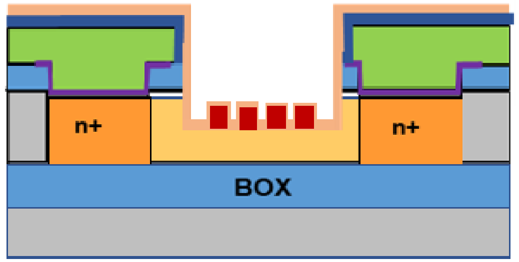


Nature Comm. 12, 1225 (2021)

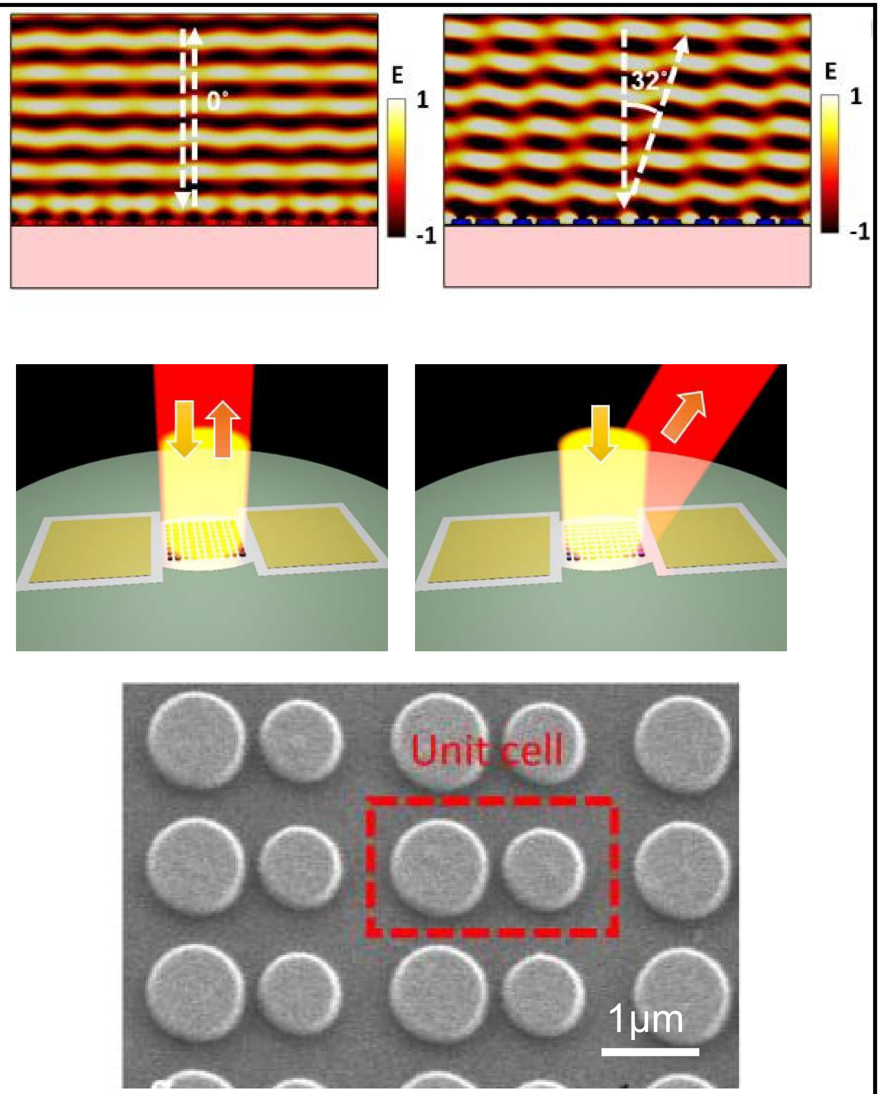
Packaged PCM metasurface devices



Metasurface pattering on PCM

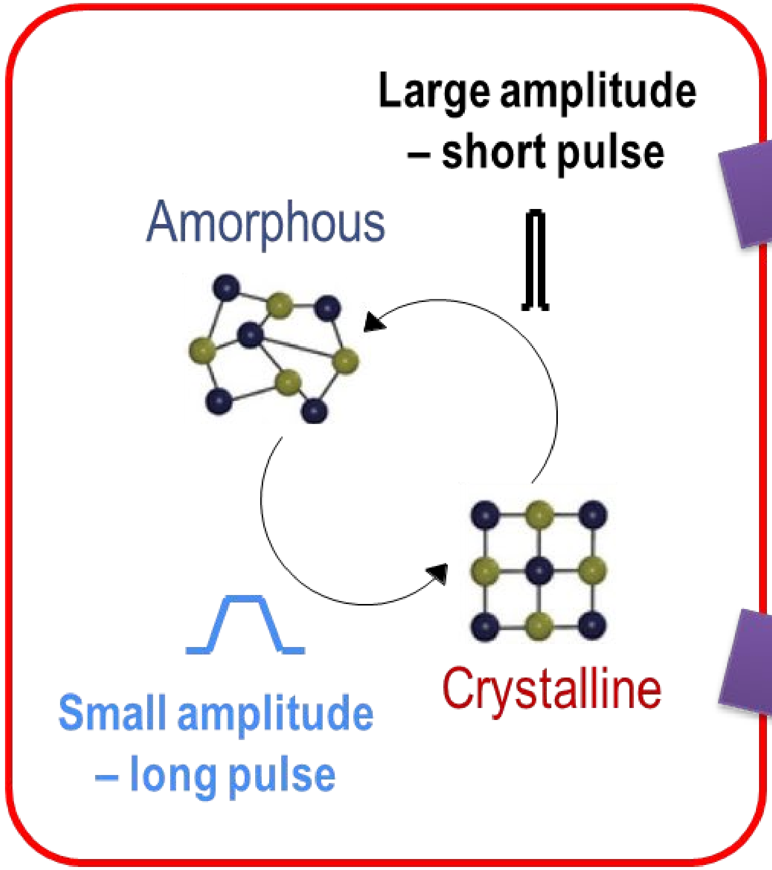


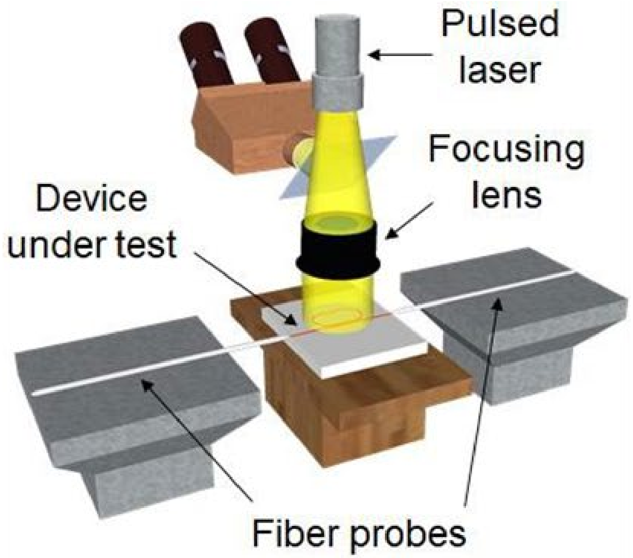
Nature Comm. 10, 4279 (2019)



Nature Nanotech. 16, 661 (2021)

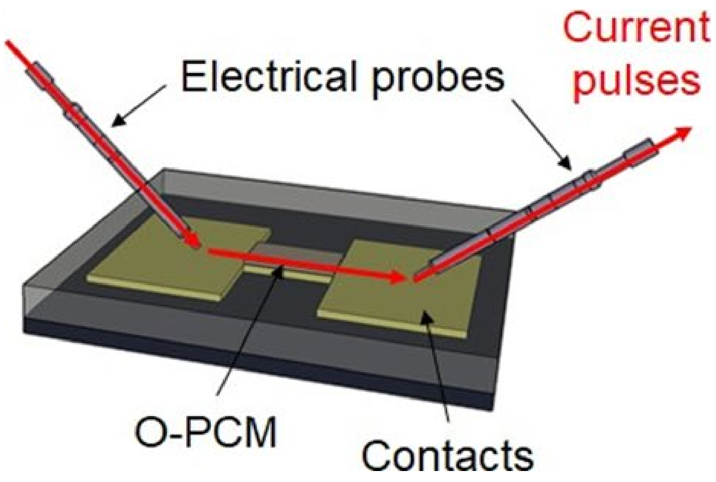
Optical and electrical switching of PCMs



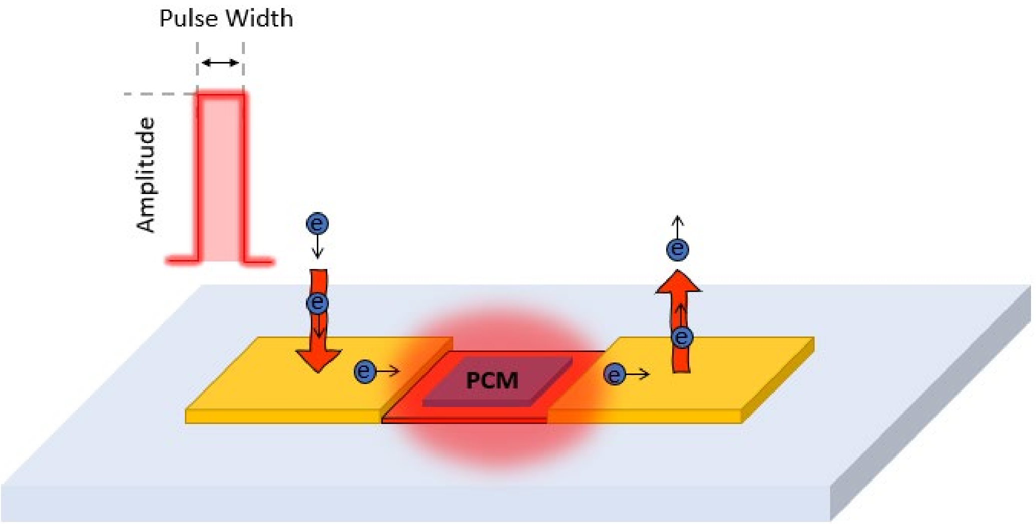


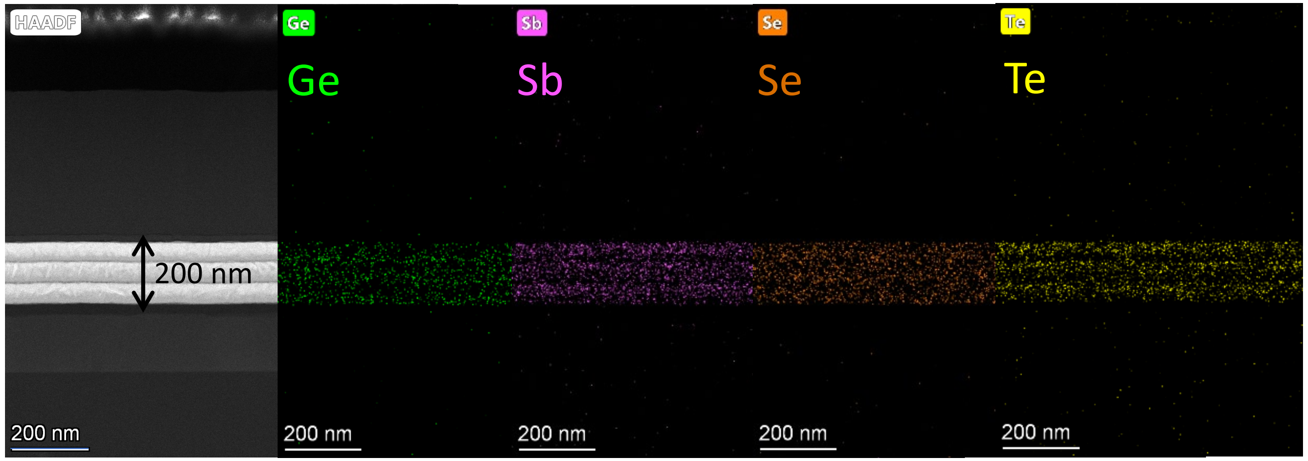
Optical (laser) switching

Electro-thermal switching

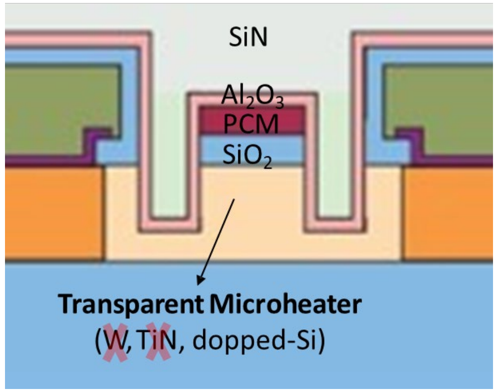


Switching PCM via electrical pulses



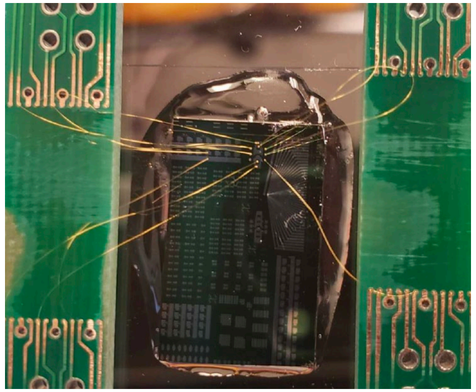


Device Architecture



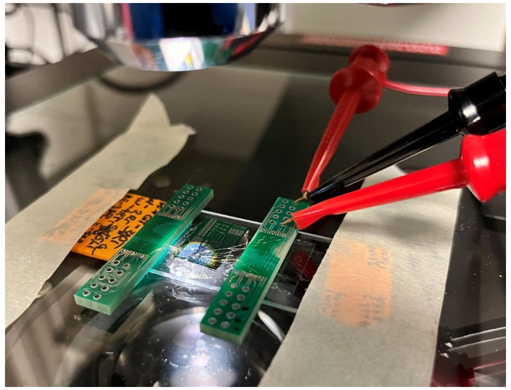
Electrode design change and different encapsulation employed

Fabrication



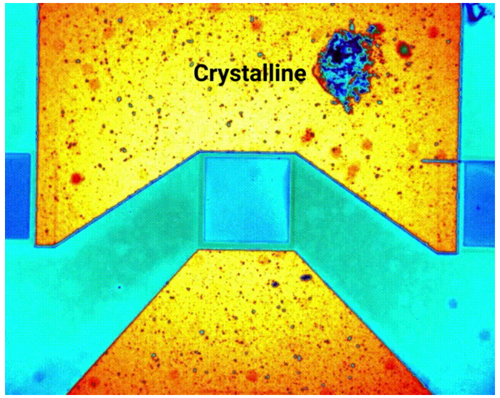
Prototype with electrode heater

Measurement



Polished sample for transmittance testing

Evaluation

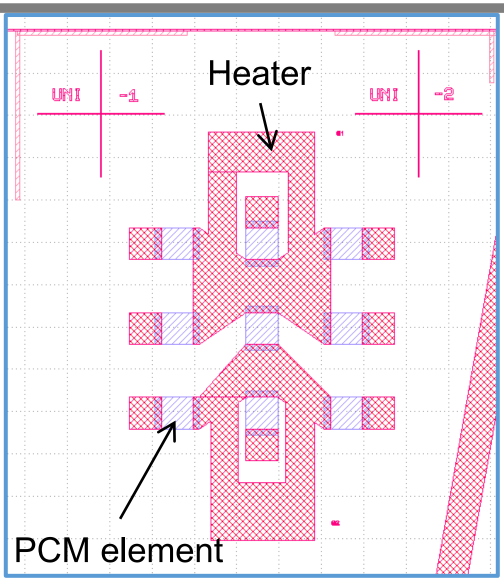


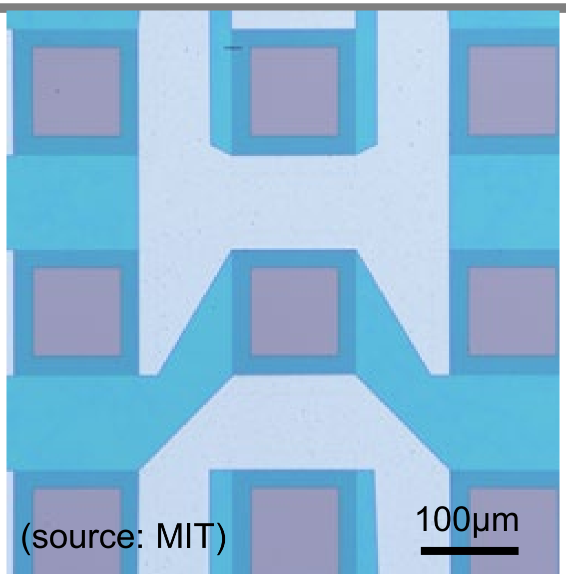
> 35,000 switching cycles demonstrated

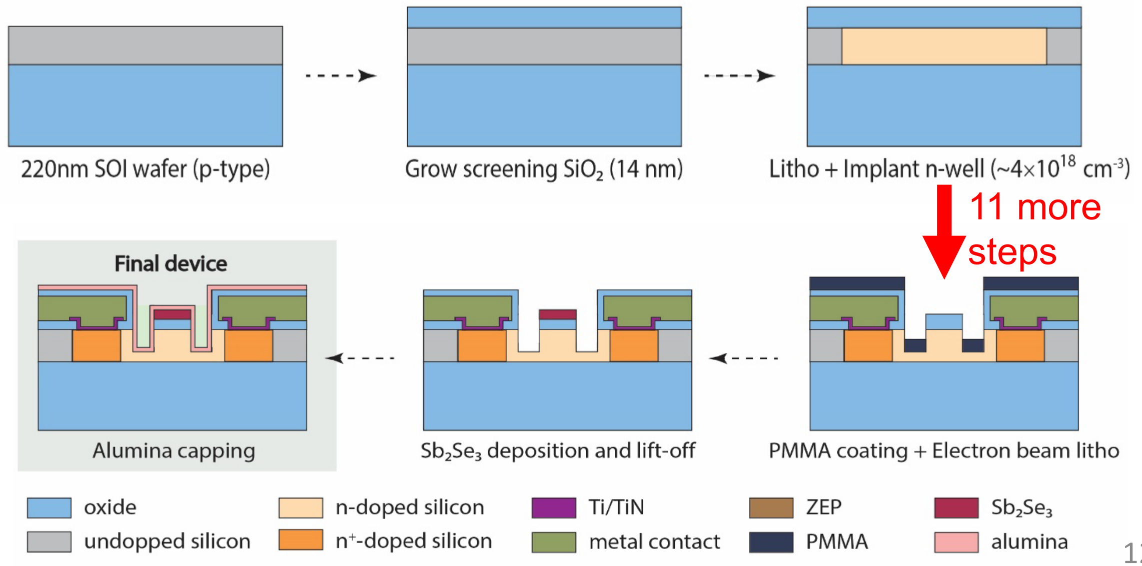
Design and fabrication of heater array

- A universal reconfigurable meta-optics/photonics array integrating phase change materials (PCM)
- Programmable 2-D high-density matrix for element-level arbitrary optical property manipulation
- Array of elements containing silicon heaters with PCMs and integrated diode selectors and cross-bar electrical connections
- Scalable, CMOS-compatible manufacturing

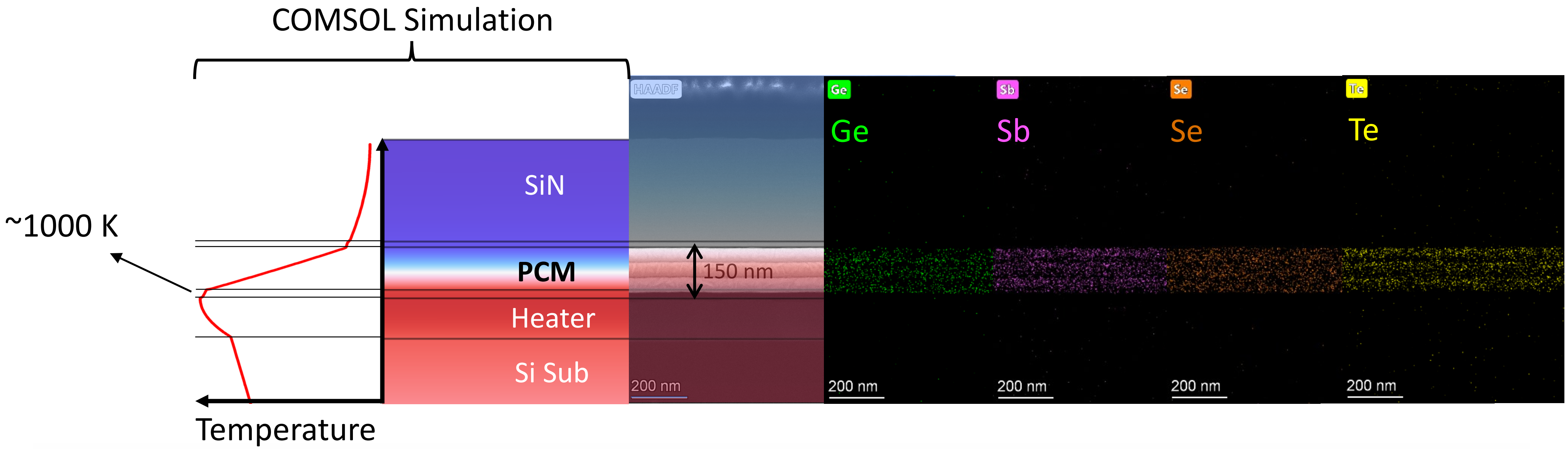
Design Specs:
- Wavelength = 1000 ~ 2000 nm
- PCM Element Size = approx. 160 microns
- PCM Element Pitch = approx. 163 microns

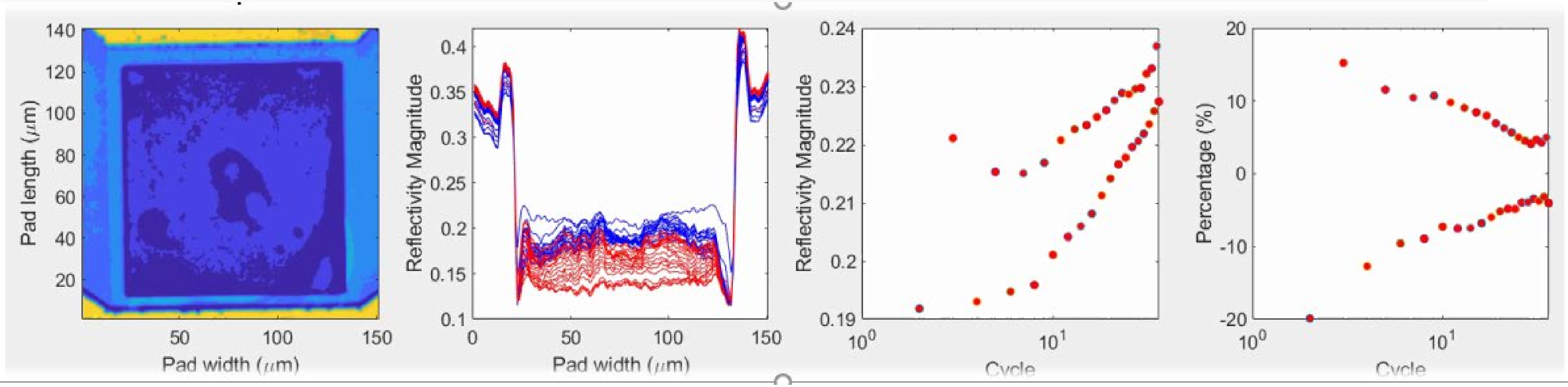






Durability and source of failure





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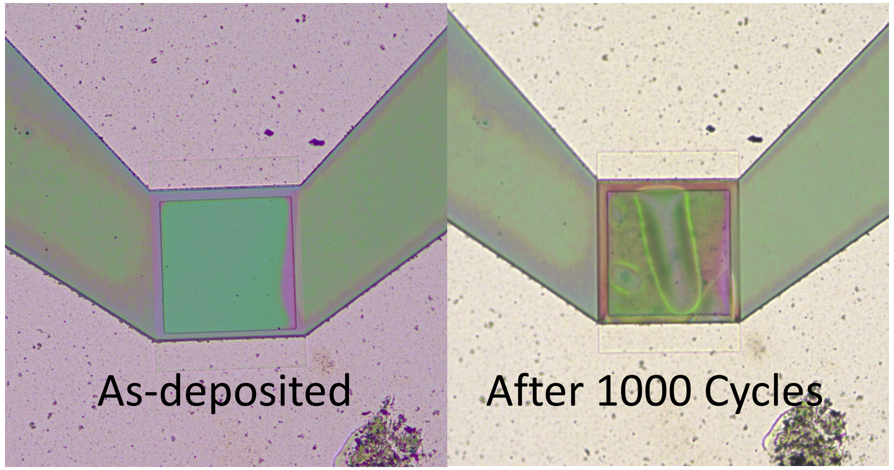
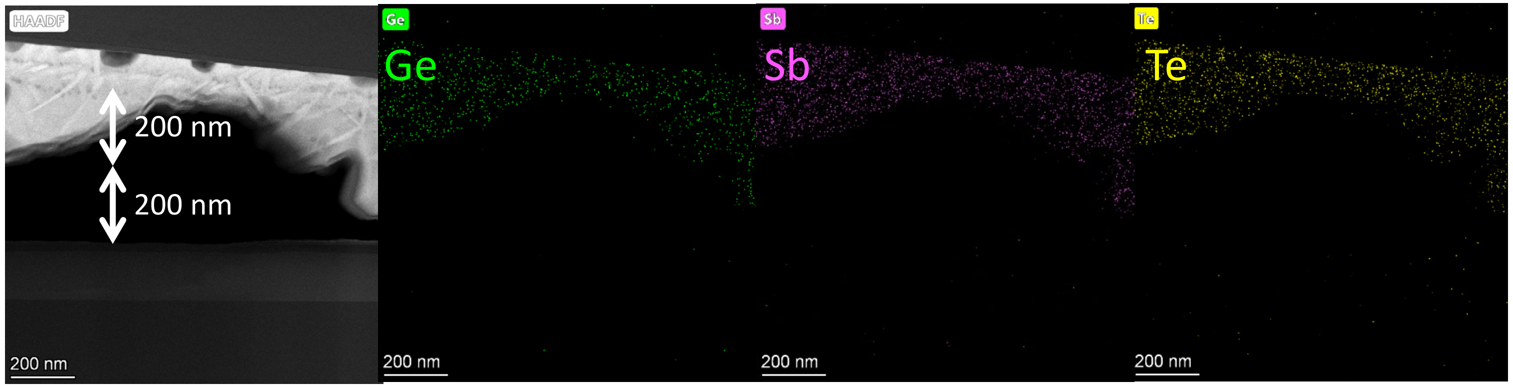
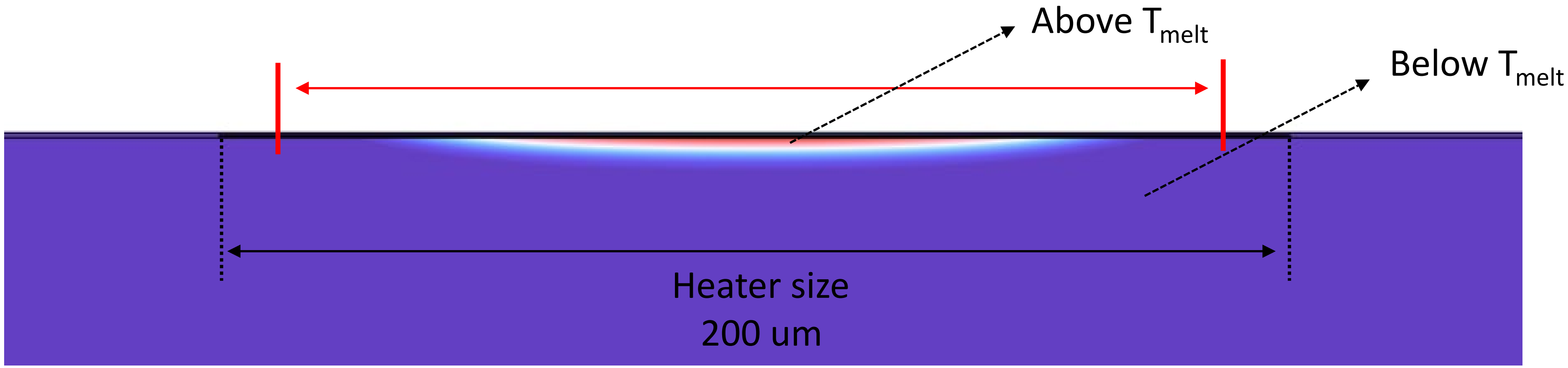
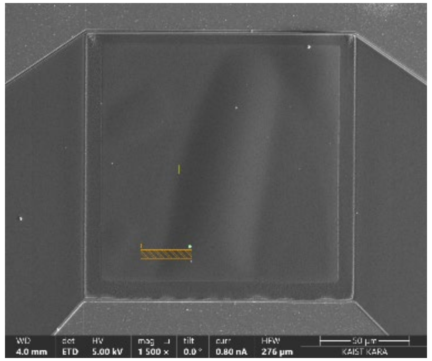
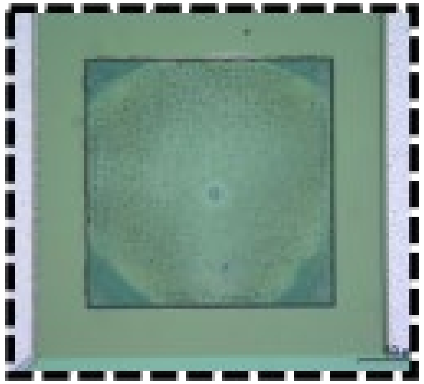




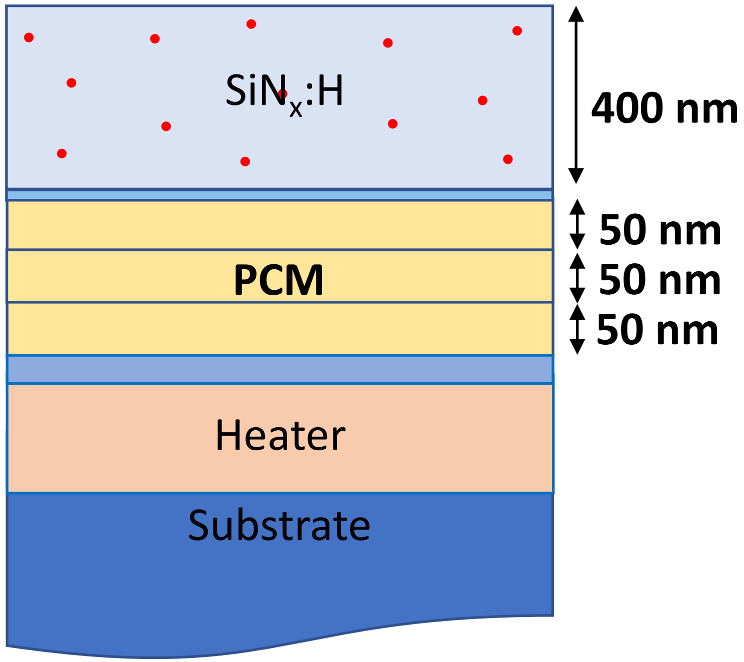






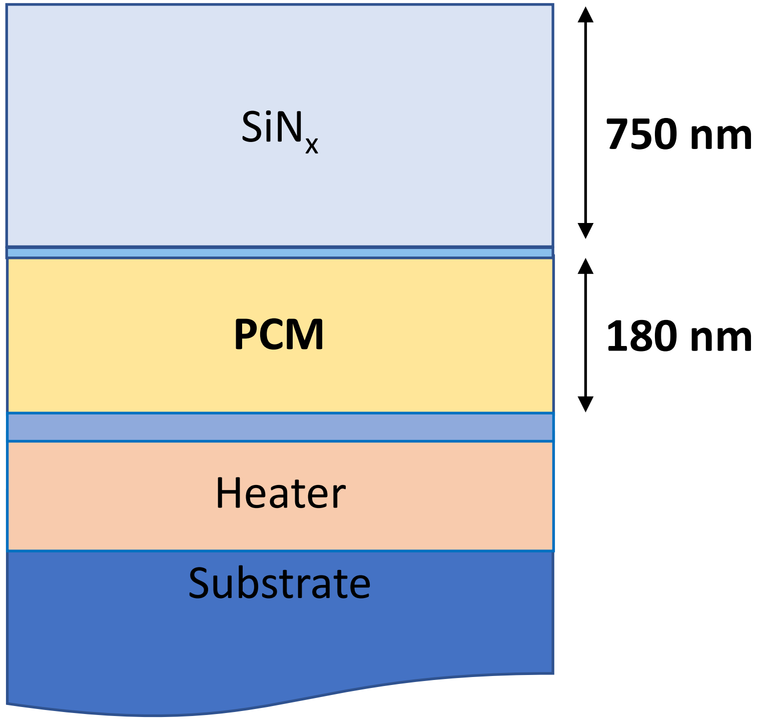
Improving the device performance

Batch - 01



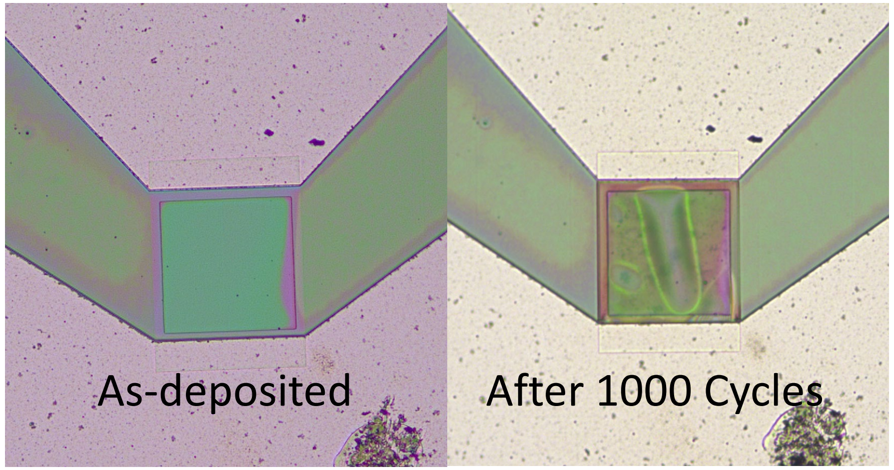
- SiN_x → PECVD
- SiN_x → with H content
- SiN_x → ~400 nm
- PCM → 3 deposition
- Al_2O_3 → 110 °C

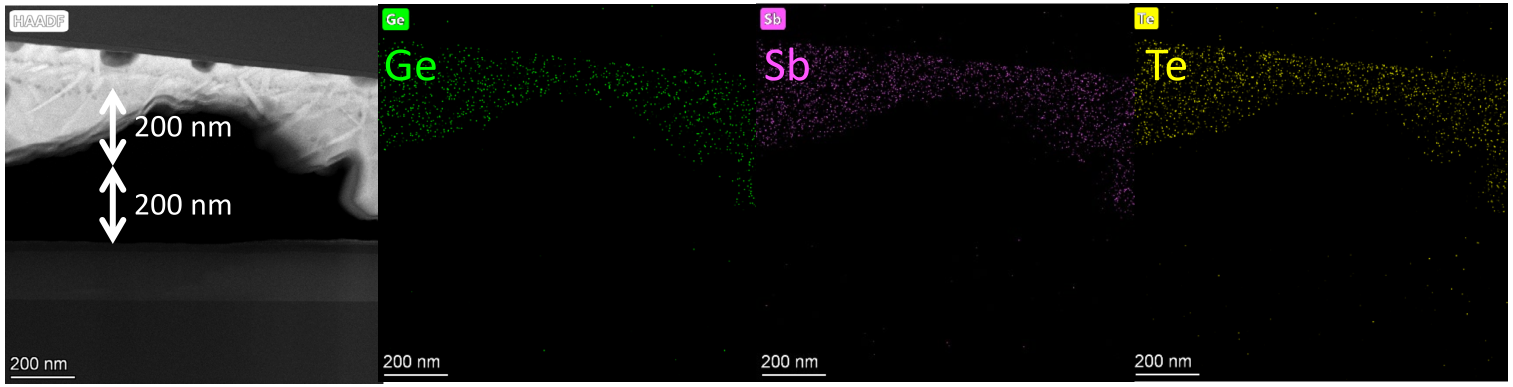
Batch - 02

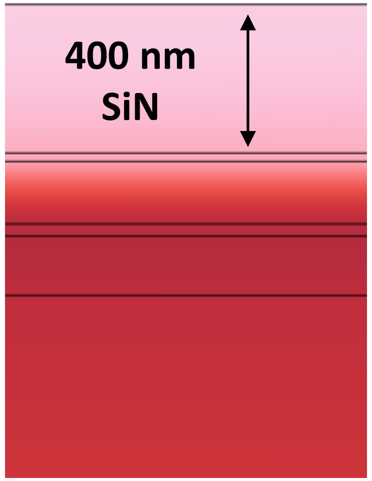


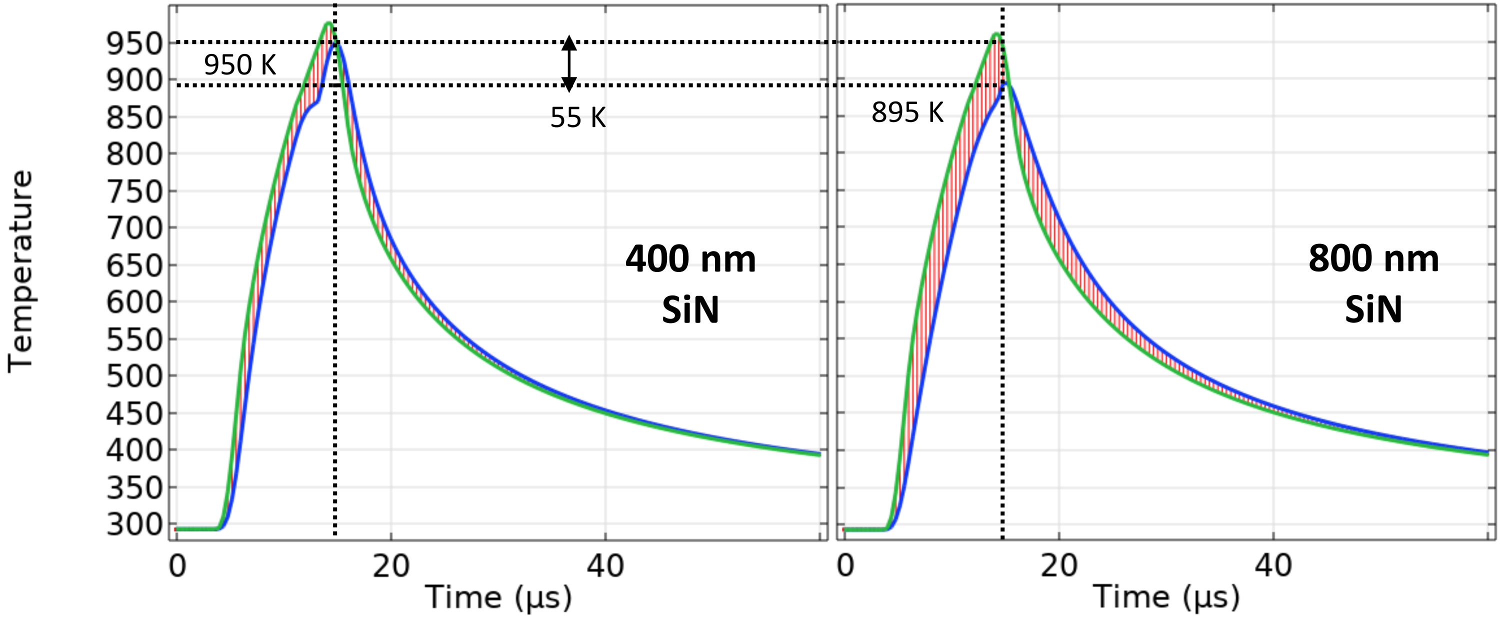
- SiN_x → Sputtered
- SiN_x → without H content
- SiN_x → ~750 nm
- PCM → 1 deposition
- Al_2O_3 → 250 °C

Durability and source of failure

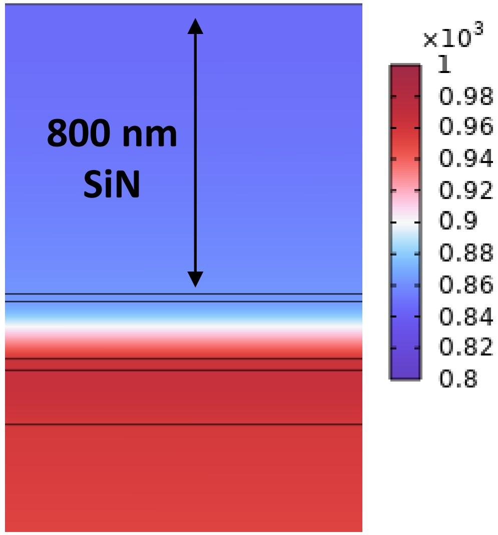




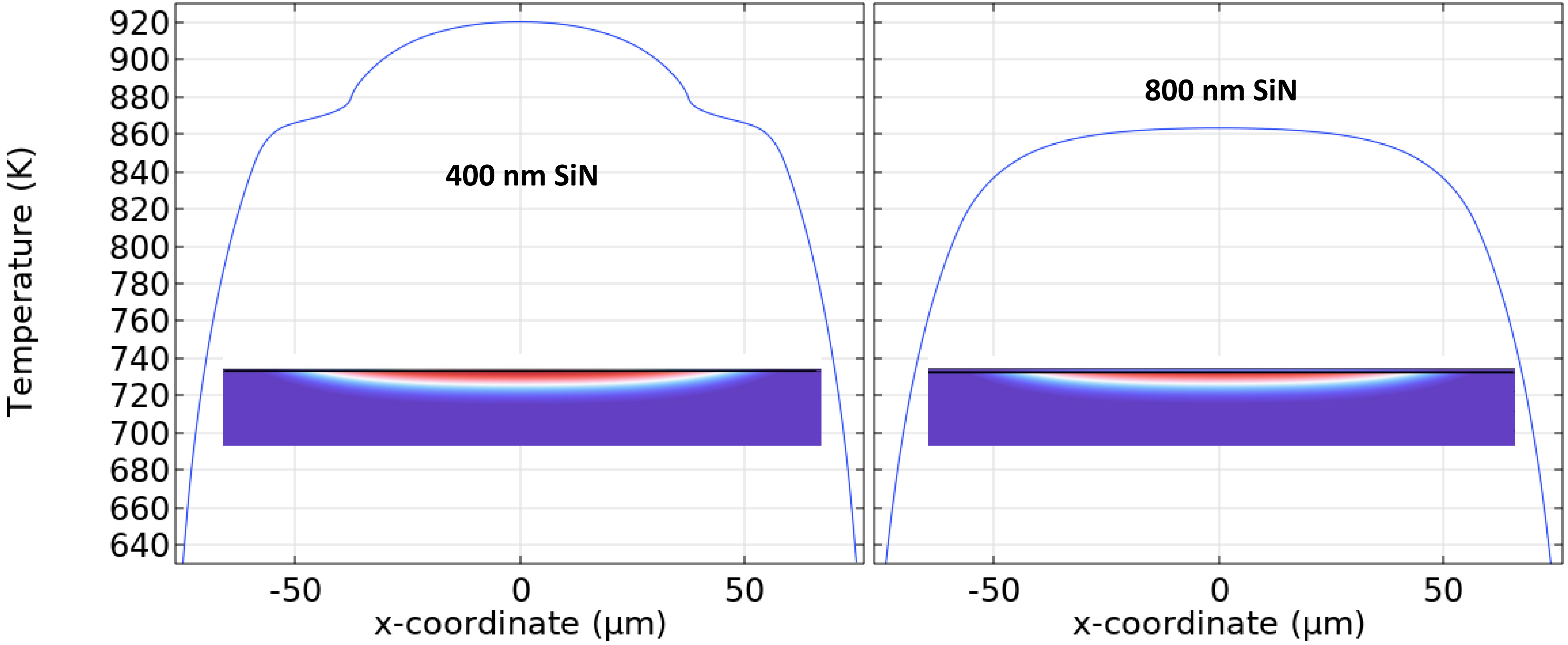




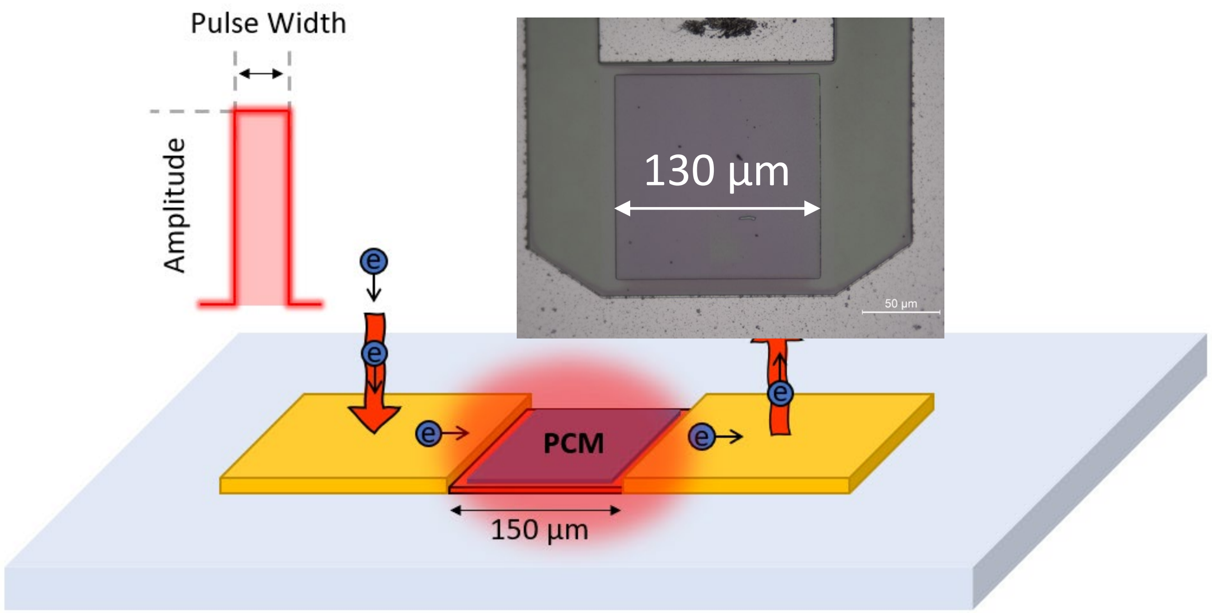
SiN$_x$ Stays cooler

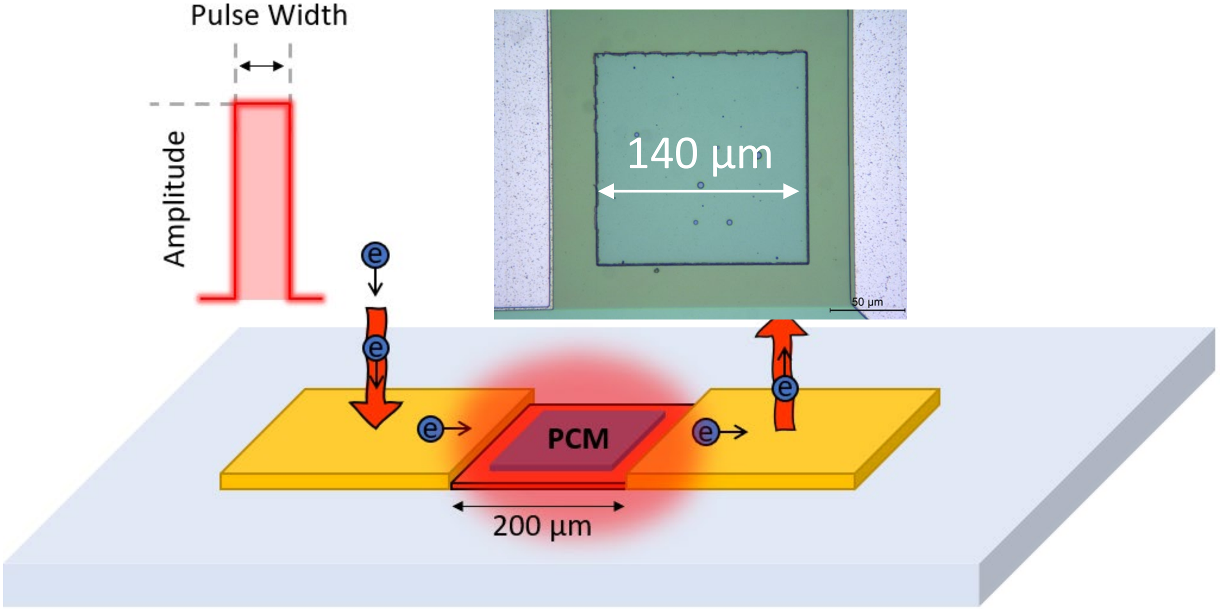


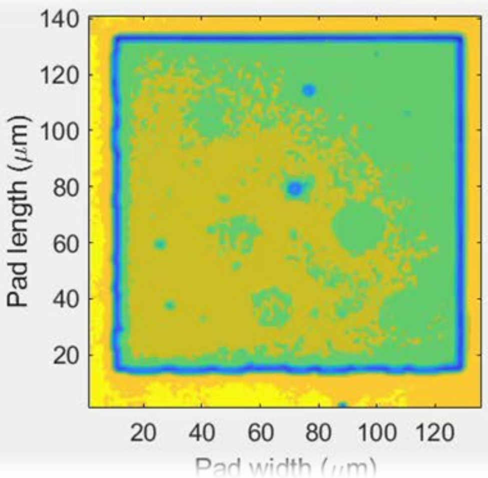
Lateral temperature distribution

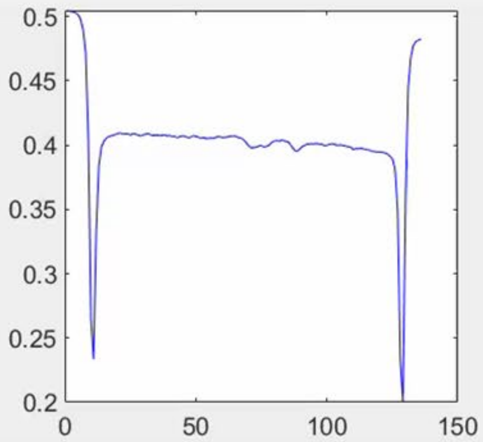


Improving the device endurance

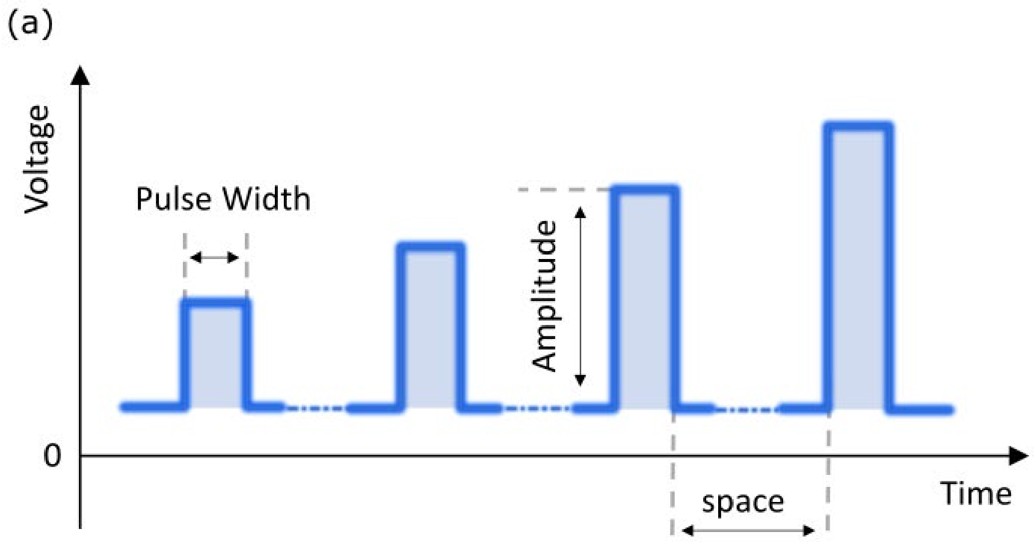


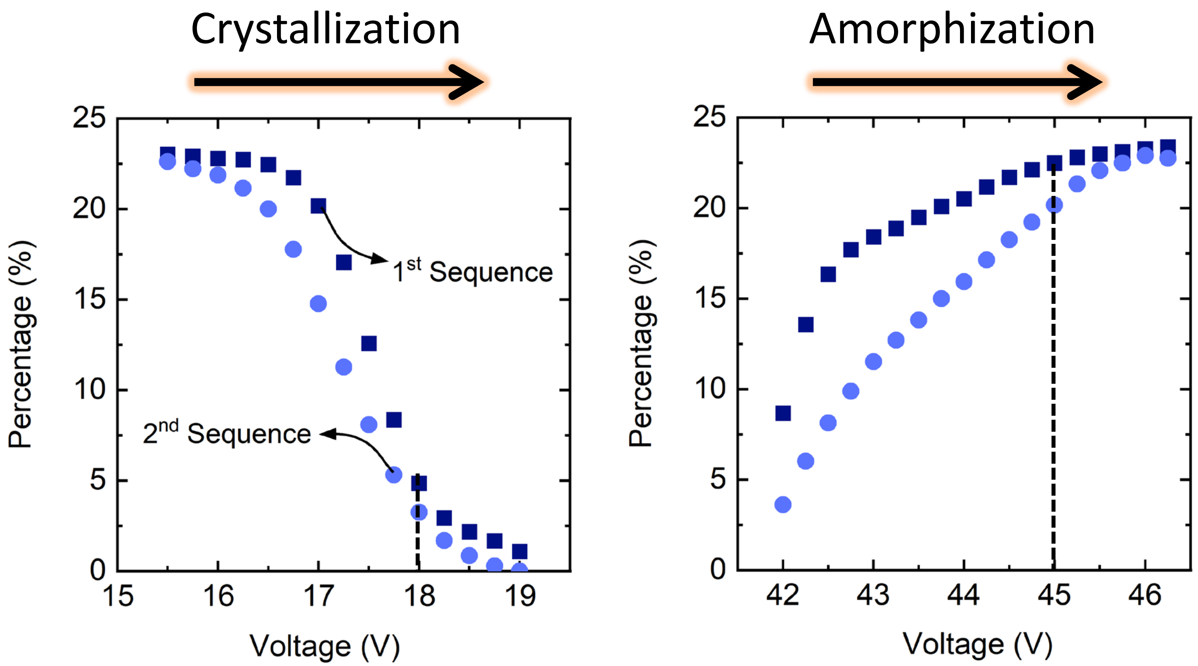


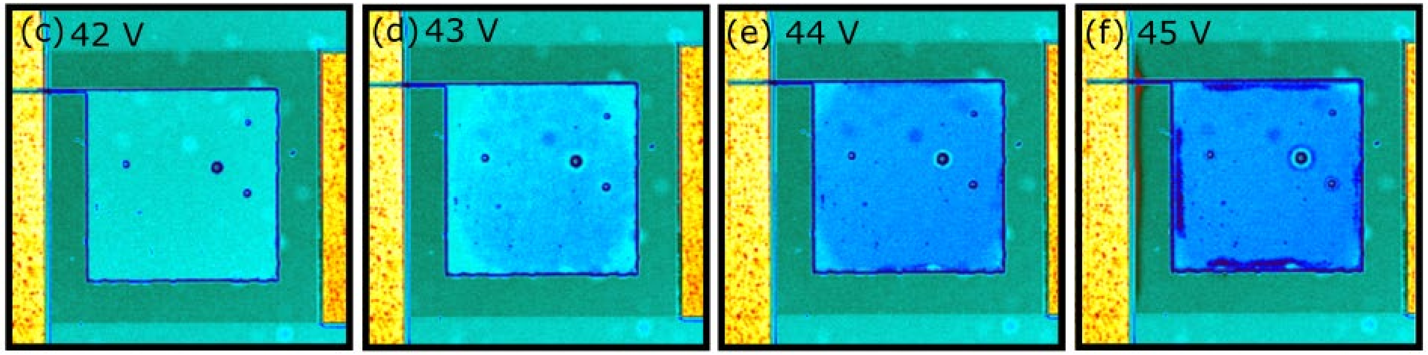


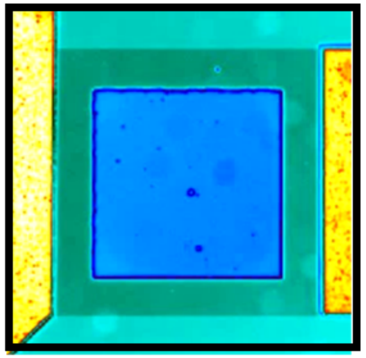


Pulse optimization



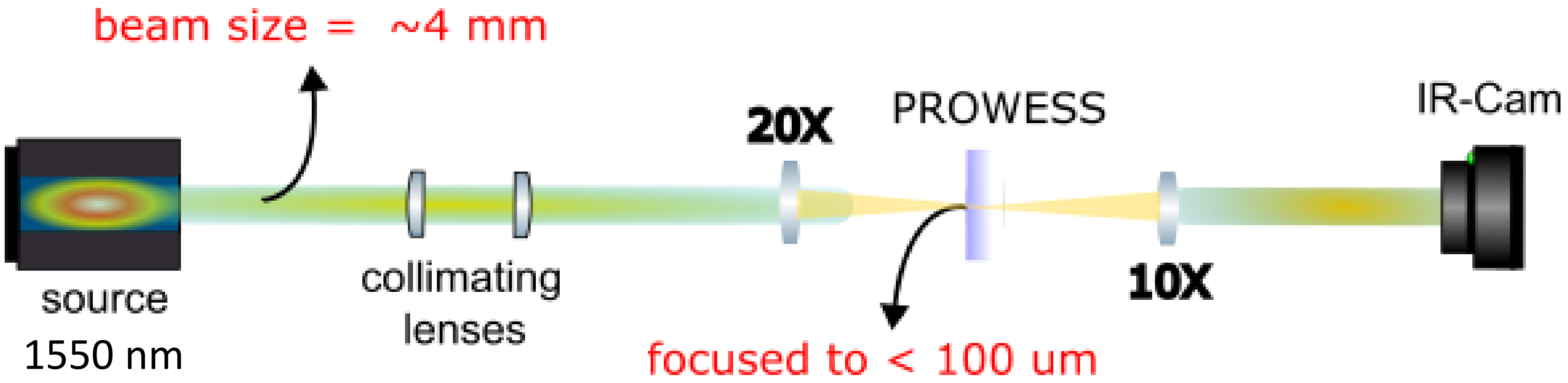


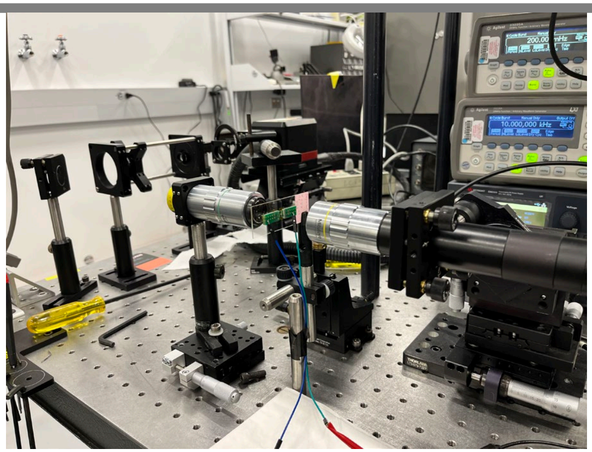


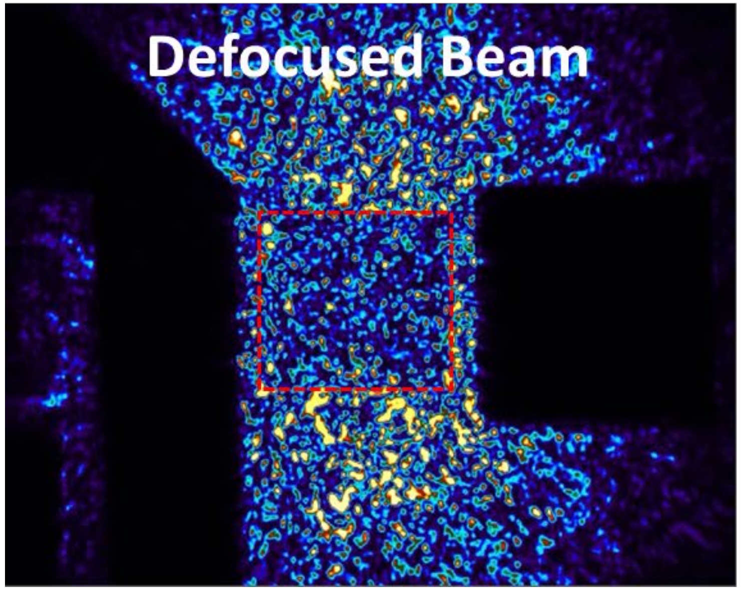


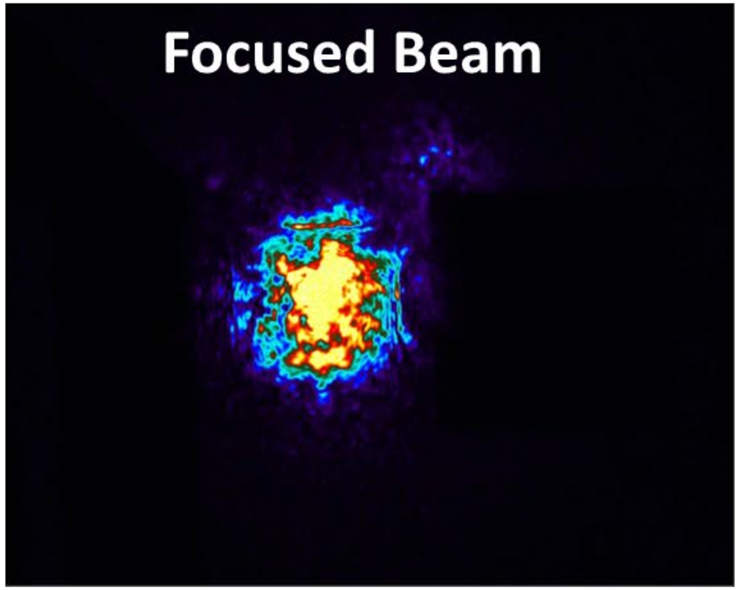
Crys: 18 V
Amor: 45 V

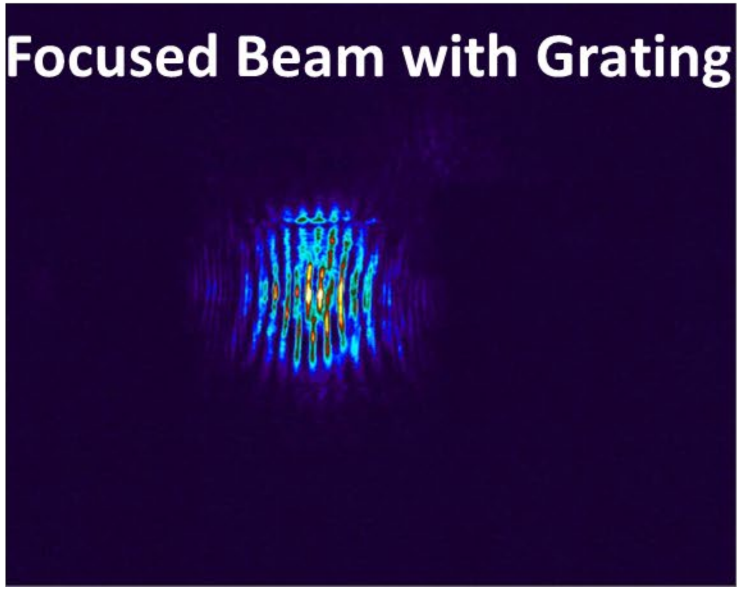
Light manipulation – No surface functionality





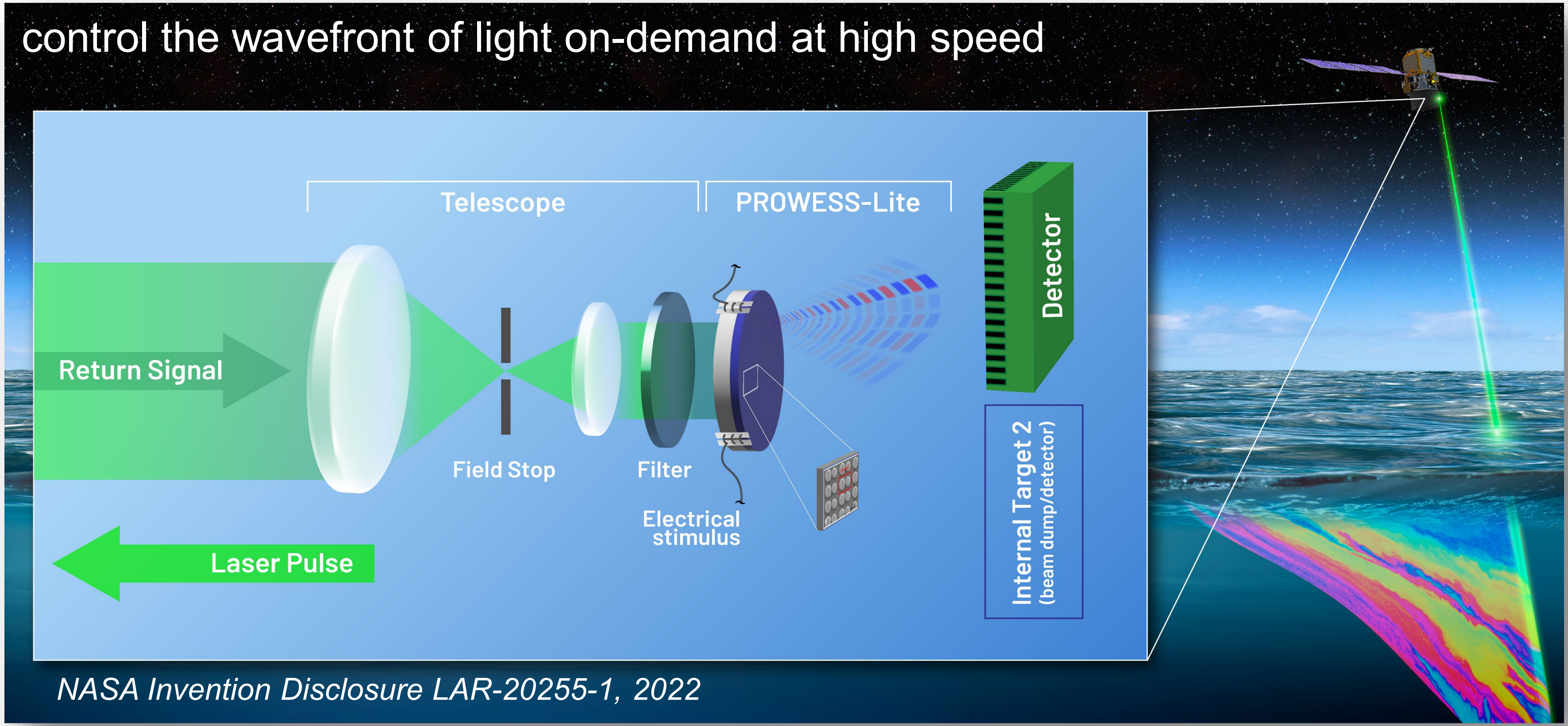






Related invited talk by Prof. Juejun Hu (MIT), 12431-36 "Learning from failure: boosting cycling endurance of optical phase change materials"
February 1, 11:00-11:30 am

Consists of sub-wavelength optical nano-antennae on PCM

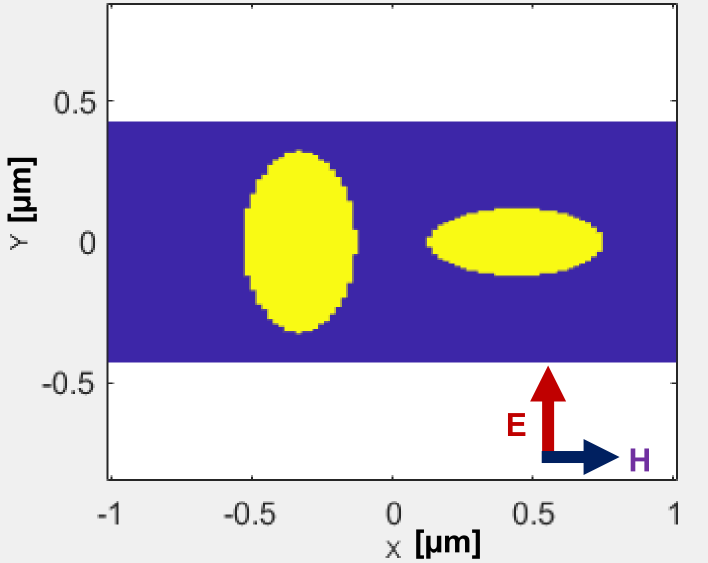


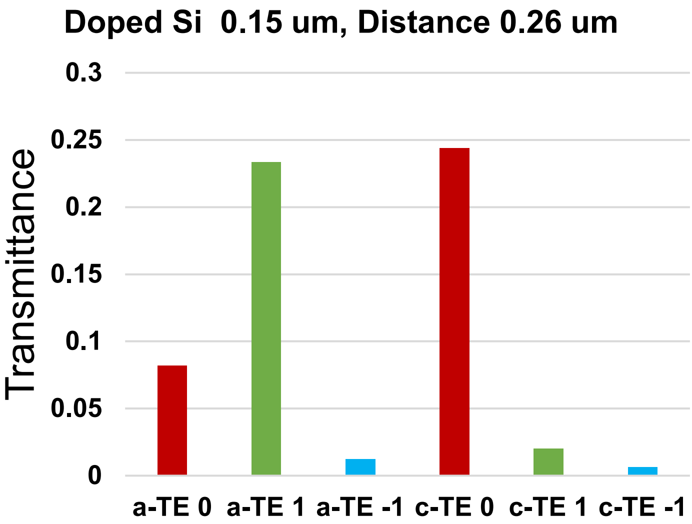
- ✓ Challenges: Existing NASA profiling lidar missions such as HSRL, CALIPSO, ICESat, and MPL all share challenges about detector system performance and recovery from bright scenes. The current development approach for such lidar detection systems focuses on ultra-fast response and recovery as a major detector performance requirement driver. This leads to unique and expensive detector development projects.
- ✓ Technical improvement: PROWESS, a next-generation planar metasurface beam steerer that converts lidar backscatter waveforms into 1D images that can be captured and read out by commercially available detectors with shorter procurement lead times.
- ✓ Mission payoff: Our unique technology eliminates detector saturation and ringing from near-range optical scattering and air-ocean interfaces, reducing after-pulse effects by >10x and allows targeted observables to be more effectively recovered.

PROWESS design for 1D beam steering

Design parameters	Transmittance mode 1064nm wavelength	Explore integration of the PCM nano-antennae with a linear array of transparent doped Si micro-heaters to enable reversible electrothermal switching of the metasurface for 1D beam steering
	< 50nm tuning speed	Steering the back-reflected beam into and out of the detector path in <50ns is sufficient to block noise pulse without losing measurement data.
	Efficiency	Both transmittance efficiency and beam steerer efficiency (switching efficiency between two orders) need to be consider for design. By optically eliminating undesired high intensity short duration pulses, >10x after-pulse reduction need be achieved.
	Polarization insensitive	Distinguished aerosol species requires measurements such as depolarization ratio, thus preserving polarization information is key.

- Period X = 2 μm
- Period Y = 0.855 μm
- Meta-atom size
    - a_1 = 0.4 μm, b_1 = 0.64 μm
    - a_2 = 0.62 μm, b_2 = 0.24 μm
- Meta-atom distance = 0.26 μm
- Doped Si thickness = 0.15 μm
- Protective cladding (SiO_2) = 0.74 μm
- PCM (Sb_2Se_3) thickness = 0.3 μm





PROWESS in space is critical for enabling next-step astrophysics and planetary science and space exploration missions

CHALCOGENIDE PHASE-CHANGE MATERIALS: CHANGING OUR APPROACH TO AEROSPACE PHOTONICS

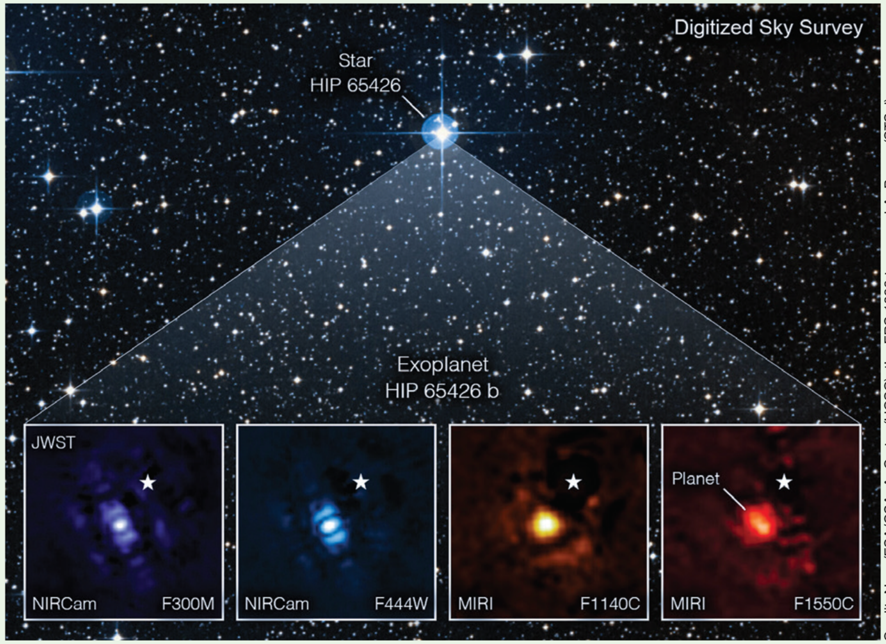
By Lisa McDonald

As we continue to push the limits of space exploration and travel, demands on next-generation space systems will increase while being constrained by lean SWaP-C (size, weight, power, and cost) budgets. Realizing subsystems that meet such performance demands requires novel photonic material platforms. Chalcogenide phase-change materials (PCMs) such as GeSbTe, GeSbSeTe, and SbTe demonstrate great potential to fulfill these needs.

Chalcogenide PCMs have the ability to repeatedly switch between two distinct, nonvolatile solid phases: crystalline and amorphous, where the crystalline phase demonstrates high conductivity and reflectivity and the amorphous phase demonstrates low conductivity and reflectivity. There is widespread use of chalcogenide PCMs in commercial nonvolatile memory devices. However, investigations into its potential photonic applications—such as tunable filters, active metaoptics, and switchable fiber-optics—picked up rapidly in the past decade.[a]

The small size, weight, and power metrics of chalcogenide PCMs promise reconfigurable optical systems that are ultracompact, lightweight, energy-efficient, and have rugged characteristics, which are highly prized in the space industry. Possible future applications of chalcogenide PCMs in space applications include

- Photonic integrated circuits, such as used for high-speed communications and sensing;
- LIDAR and imaging spectroscopy components, for example, spatial light modulators, beam steerers, and tunable filters;
- Deep-space imaging, including autofocus/real-time phase-corrective lenses and planar adaptive optics; and



Credit: Nasa/ESA/CSA, A. Carter (UCSC), the ERS 1386 team, and A. Pagan (STScI)

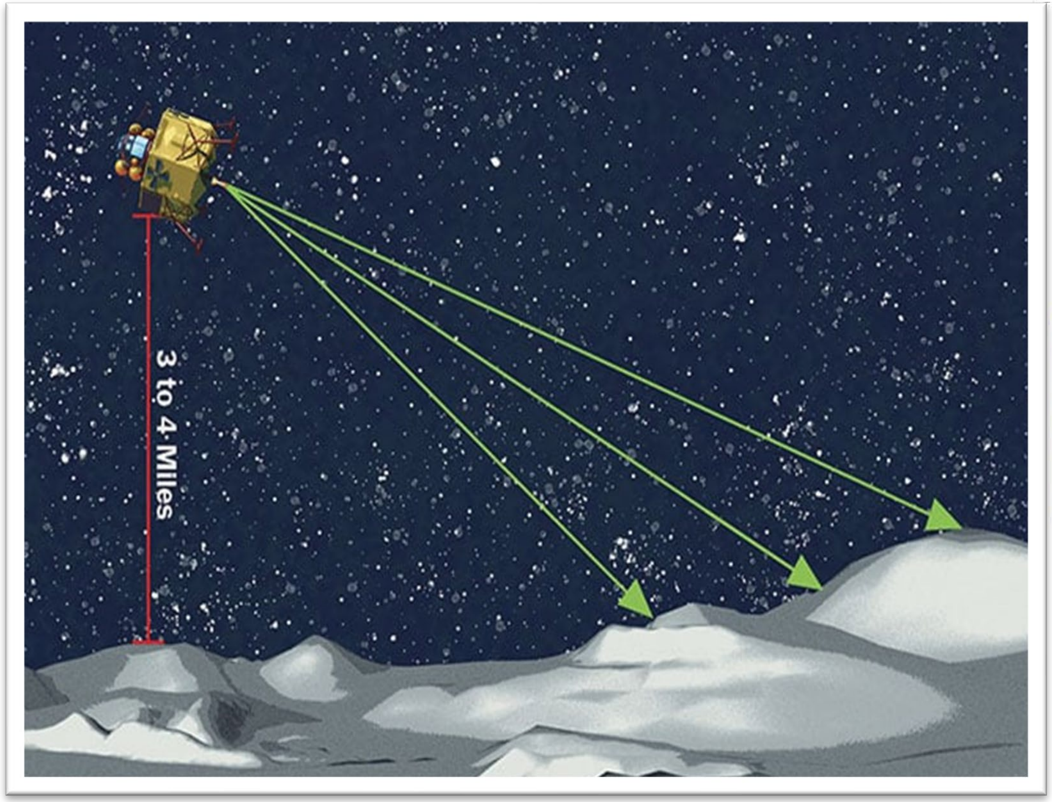
Image of a gas giant exoplanet by the James Webb Space Telescope, as seen through four different light filters. Space-based exoplanet imaging requires real-time wavefront corrections to lessen the effects of thermal gradients, optical imperfections, and diffraction issues. Chalcogenide PCMs could be used to simplify the correction system.

- Satellite temperature management/thermal homeostasis, such as tunable/dynamic thermal emission control.

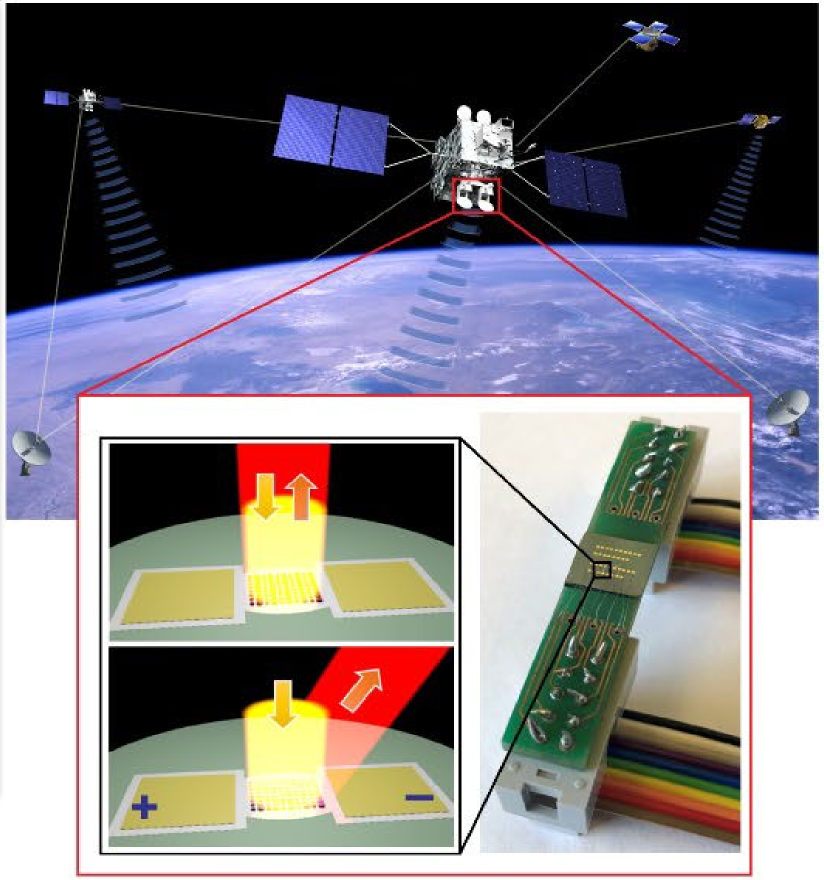
To advance commercialization of optical PCM devices, improving cycle lifetime is a main focus. While endurance and failure mechanisms are extensively characterized for PCMs in electronic applications, much effort is still required to fully validate optical PCM longevity.

[a] "L. Martin-Monier, C. C. Popescu, L. Ranno, et al., "Endurance of chalcogenide optical phase change materials: a review," *Optical Materials Express* 2022, **12**(6): 2145–2167.

PROWESS for space explorations (safety & science)



Navigation Doppler Lidar for Moon landing
Photo Credit: Psionic LLC
Ref: Optics Express 24 (3), #255741 (2016).

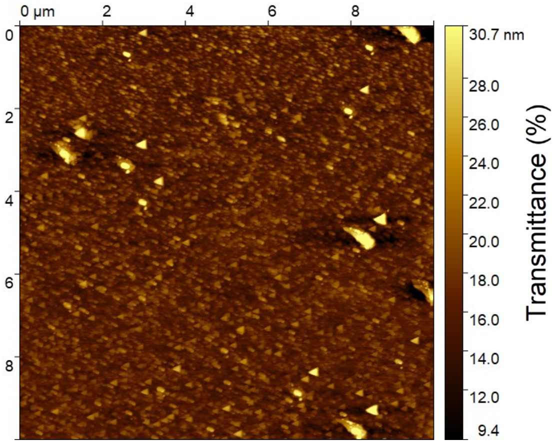


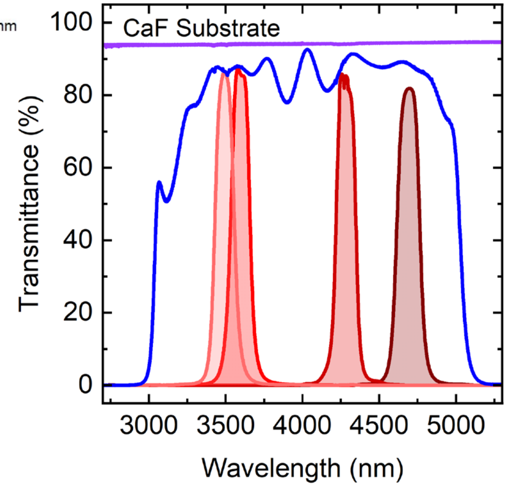
PCM reconfigurable optics for wavefront correction and beam steering
Ref: Nat. Comm. **12**, 1225 (2021).

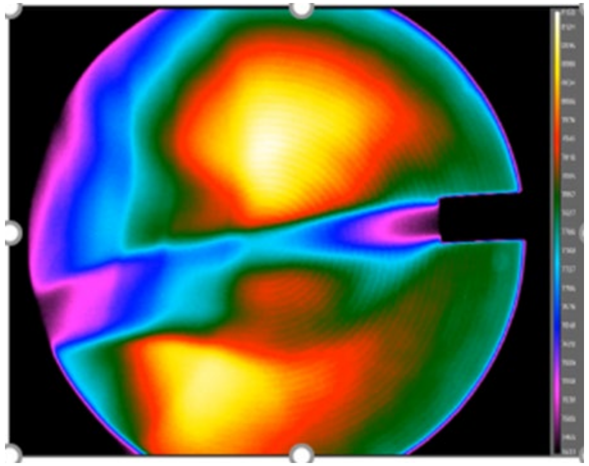
Space docking to ISS
Photo Credit: NASA

PCMs in ISS through MISSE-14 test campaign

- MISSE - Materials International Space Station Experiment – materials and devices exposed to the space environment (LEO, space below an altitude of 2,000 km), atomic oxygen, -120 °C to 120 °C temperature extremes, hard vacuum, UV radiation, charged-particle radiation (electrons, protons, light ions, heavy ions, etc.)





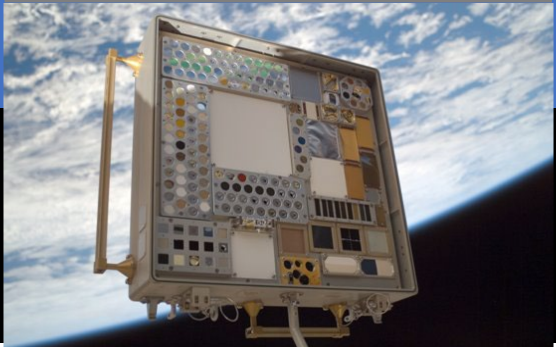


Launch
02/20/2021
- Preparation
- Preflight characterization

Unpack / unsealing
04/08/2021

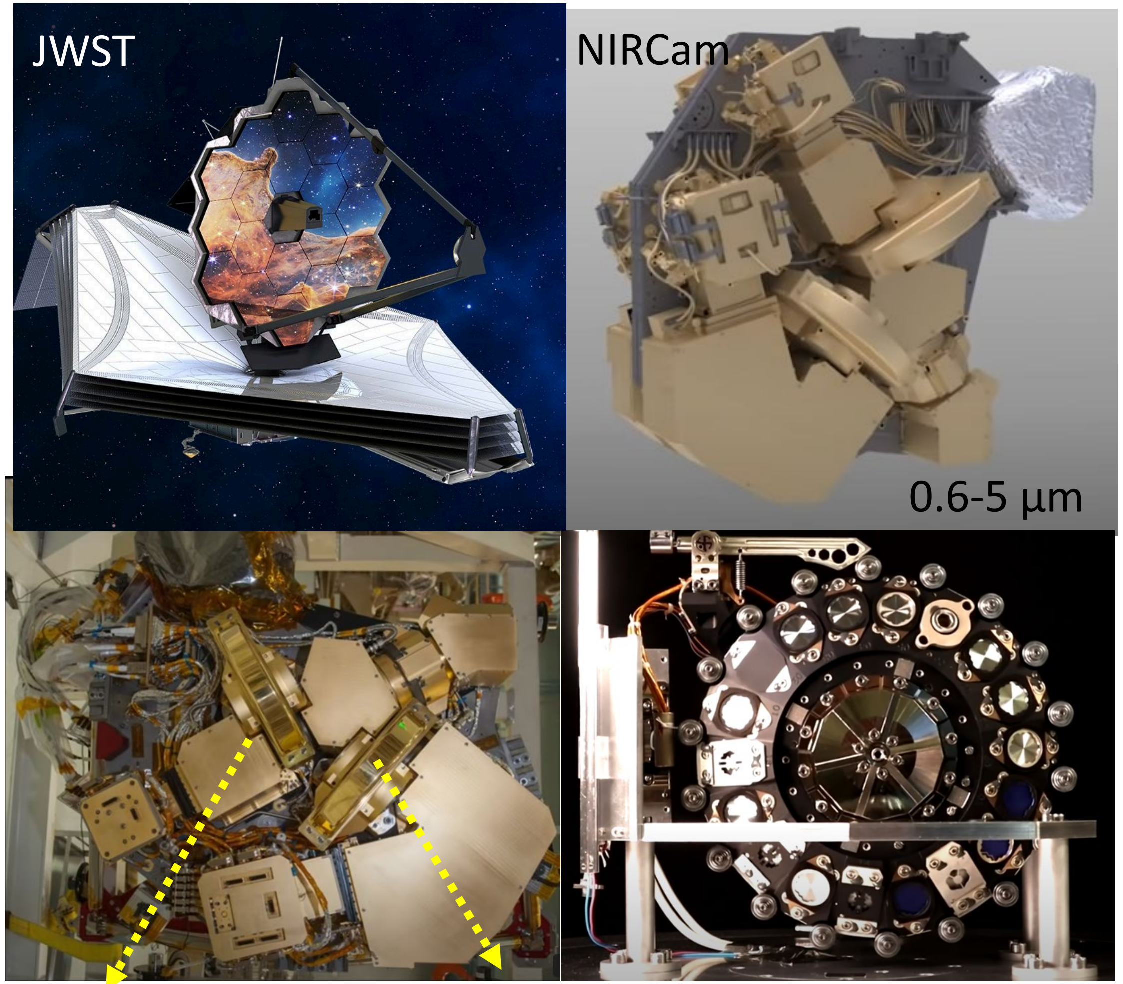
Deployment on orbit
04/25/2021

Exposure & monitoring
06/21/2021-12/6/2021
(148 days 21 hours 11 minutes)



Return
01/25/2022
- Retrieval
- Post flight characterization

Tunable optics for space explorations



Long Wavelength Filter Wheel

Short Wavelength Filter Wheel

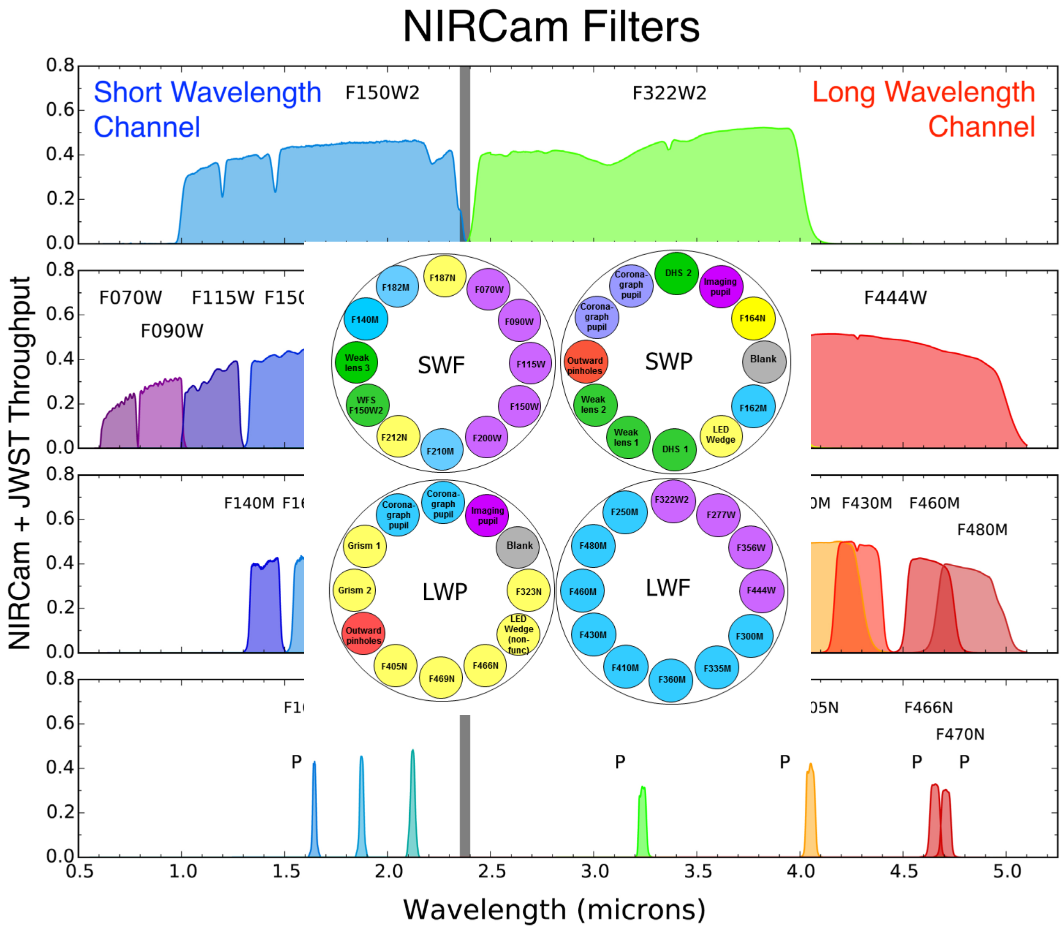
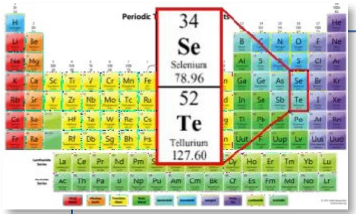


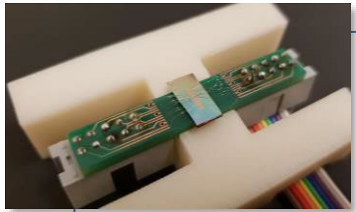
Photo Credit: NASA

Related talk by Dr. Kiumars Aryana, 12417-3 “Effects of LEO space exposure on GeSbTe phase-change metasurface spectral filters”
January 30, 11:20-11:40 am

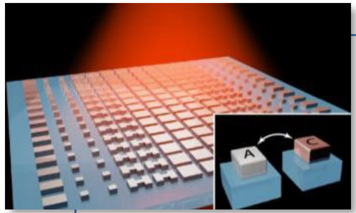
Summary



With its low optical loss, large index change and switching volume, PCM is an ideal material for active metasurfaces



Understanding and mitigating failure mechanisms enable electrical switching of PCM metasurfaces over tens of thousands of cycles (and likely more)



Refractive mode PROWESS was demonstrated, and transmittance mode is realized for the first time for NASA science mission scenario

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